The Final Report

Title: Information Fusion for Hypothesis Generation under Uncertain and Partial Information Access Situation

Principal InvestigatorI: Dr. Hiroaki Kitano
ZMP Incorporated, Tokyo, Japan

Contract Number: FA520904C0003

AOARD Reference Number: AOARD-034-035

AOARD Program Manager: Tae-Woo Park, Ph.D.

Period of Performance: 28 August 2001 – 6 July 2005

Submission Date: 21 July 2006

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
31 OCT 2008	**Final**	**28-08-2001 to 06-07-2005**

4. TITLE AND SUBTITLE
Information Fusion for Hypothesis Generation under Uncertain and Partial Information Access Situation

5a. CONTRACT NUMBER
FA520904C0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Hiroaki Kitano

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ZMP Incorporated,7F Katsuta Bldg, 1-3-39, Mita, ,Minato-ku,Tokyo, Japan,NA,108-0073

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AOARD, UNIT 45002, APO, AP, 96337-5002

10. SPONSOR/MONITOR'S ACRONYM(S)
AOARD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AOARD-034035

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The challenge for most artificial systems that operate autonomously in the real world environment is how to cope with dynamic environment with limited, uncertain, and noisy information. Artificial intelligence and intelligent robotics research has been trying to solve such a problem by either improving accuracy of recognition systems or by integrating multiple source of information. In addition, architectural issues has been discussed on whether classical Sense-Model-Plan-Act architecture or the subsumption architecture better suits for autonomous agents. Information fusion issue is tightly coupled with behavioural control as overall performance of the autonomous system is the ultimate concern. The work performed focused on identifying possible system architecture for realistic information fusion and corresponding reactions under uncertain environments. Our research starts from analysing issues in existing paradigm of autonomous agent and AI architectures, redefine needs, and propose a suitable architecture. In this research, it was essential to learn from biological systems where various species has evolved to adapt to uncertain and dynamic environment for survival.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**82**	

Contents:

Publications:

P.1. Kitano, H., Kaminaga, H., and Landerman, J., Robust Architecture for Dynamical Environments, FUSION 2004, 2004.

P.2. Kitano, H., Challenges in Robust Situation Recognition through Information Fusion for Mission Criticial Multi-Agent Systems, Proceeding of RoboCup-2003, Springer-Verlag, 2004.

P.3. Kitano, H., Oda, K., Kimura, T., Matsuoka, Y., Csete, M., Doyle, J., Muramatsu, M.. Metabolic Syndrome and Robustness Tradeoffs, Diabetes 53, S6-S15, 2004

P.4. Kitano, H., Biological Robustness, Nature Review Genetics. 5, 826-837, 2004

P.5. (5) Kitano, H. Cancer as a Robust System: Implications for Anticancer Therapy, Nature Reviews Cancer. 4, 3, 227-235, 2004

Executive Summary

1. Introduction

The challenge for most artificial systems that operate autonomously in the real world environment is how to cope with dynamic environment with limited, uncertain, and noisy information. Artificial intelligence and intelligent robotics research has been trying to solve such a problem by either improving accuracy of recognition systems or by integrating multiple source of information. In addition, architectural issues has been discussed on whether classical Sense-Model-Plan-Act architecture or the subsumption architecture better suits for autonomous agents. Information fusion issue is tightly coupled with behavioural control as overall performance of the autonomous system is the ultimate concern.

The work performed focused on identifying possible system architecture for realistic information fusion and corresponding reactions under uncertain environments. Our research starts from analysing issues in existing paradigm of autonomous agent and AI architectures, redefine needs, and propose a suitable architecture. In this research, it was essential to learn from biological systems where various species has evolved to adapt to uncertain and dynamic environment for survival.

2. Limitations of Current Architectures

2.1. Robustness of Sensing Systems

There are several approaches proposed to provide intelligent and autonomous behaviours interacting with real-world environment. In this article, “real-world environment” refers to physical real world with open dynamics that is, in general, outside of the laboratory space. In such environment, numbers of unexpected incidents may take place that are not expected at the time of system design. One of the problems for man-made systems is its inherent fragility against unexpected perturbations that are not designed for. Major efforts have been made to improve accuracy of recognition for vision and audition, but mostly for a single modality of perception. For example, vision systems are often designed to recognize object based on shape of objects based on image captured by the camera. Some other systems focus on color or pattern matching with stored images. It was relatively recent that efforts are made to integrate information from multiple sources, and such efforts are made only between two or three types of modalities. Our previous work discovered that accuracy of each modality of perception can be improved when information in each channel is properly integrated [Nakagawa, et al, 1999; Nakadai, et al, 2000]. However, the integration has only been taken place between color-based labelling vision system with physical a priori knowledge and auditory scene analysis system. The problem of these approaches is that they may not be sufficiently robust against perturbations of signals that provide key to recognition of situation the agent is located. Shape-based visual recognition system would not work when a part of object is not visible from the camera. Color-based recognition cannot work when light level is very low for color-based recognition. While integration is effective, integration of small numbers of different modalities is not sufficiently robust against perturbations. Since the system will be used under hostile and uncertain environments, robustness shall be the major concern in the architectural design of the system. Consideration shall be given at all levels of system to enhance its robustness. Our preliminary work clearly suggested that increase of modalities significantly improve not only overall systems performance on recognition of the situation, but also accuracy of recognition within each sensory channel [Okuno, et al., 2004].

2.2: Contextual-thickness of Artificial and Biological Systems

Other significant issue for autonomous system is their high-degree of dependence for context and task assigned. Artificial systems are generally designed for specific tasks, and can be extremely effective. The champion example is computer chess which Deep Blue beats Gary Kasparov, the human world champion. However, deep blue will not be able to drive a car, clean houses, sing a song, etc. Its function is narrowly tuned. On the other hand, biological systems, typically human being, can cope with broad tasks at certain level of competence. As shown in Fig 1, biological systems are “contextually-thick” and artificial systems are not [Kitano et al., 1993].

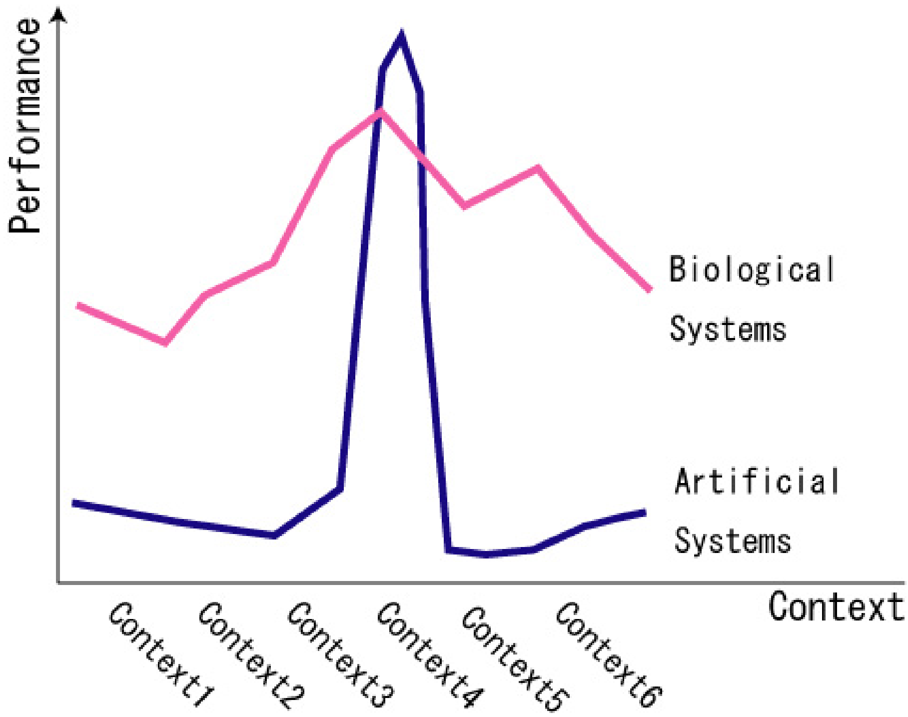
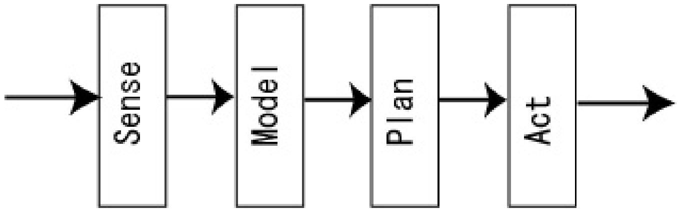


Fig 1: Contextual-thickness of systems

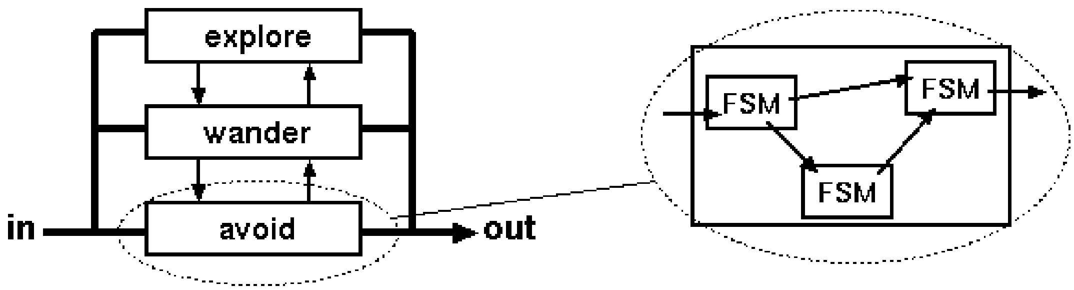
2.3 Architecture for Intelligent Systems

In addition, there has been an argument that traditional Sense-Model-Plan-Act (SMPA) architecture (Fig2a) is not suitable for autonomous system in the real-world, and alternative architecture called "the subsumption architecture" has been proposed by Rodney Brooks [Brooks, 1991]. The subsumption architecture is one of example where attempt has been made to learn from biology as it was inspired by insect behaviours during Rod Brooks's stay in a village in Thailand. The subsumptoin architecture is an attempt to use the physical real-world as a model itself without having a model of the world within the autonomous system. The idea is to hardwire sense-reaction circuits for low-level process and add layers of such processes with mostly inhibitory control (Fig 2b). It has been very successful for simple tasks, but not shown to be scalable for more complex tasks. In addition, it was not sufficiently effective in coping with multiple tasks and dynamical environment where unexpected perturbations are imposed. Each elementary behaviours are hardwired which assume a certain stimuli shall trigger a specific sequence of actions. Thus, such system lacks robustness against environmental changes.

These arguments on architecture of intelligence systems miss the point of robustness, evolvability and global properties of complex networked systems. In the author's view, these are the central issues that guides us define suitable architecture for intelligence system under uncertainty which is best investigated in biological systems that have actually evolved to survive under uncertain and dynamic environment.



(A) Sense-Model-Plan-Act (SMPA) architecture



(B) Behaviour-based AI architecture

Fig 2: Architectures for Intelligent Systems

3. Robustness is the Fundamental Issue

Robustness is a property of the system that can maintain certain properties against certain perturbations. Such properties can be observed for both artificial and biological system to different degree. However, artificial systems are nowhere near the level of robustness realized in most of biological systems. This is a strong motivation for us to closely look into robustness of biological system so that we can learn architectural features of robust systems with the hope of extracting essential and universal features.

3.1 Basic Mechanisms for Robust Systems

The system generally exhibits adaptation against changing environments and insensitivity to parametric changes. Such properties can be achieved by few basic mechanisms that are; (1) feedback control, (2) redundancy, (3) modularity, and (4) structural stability [Kitano, 2004a].

Combination of such basic mechanisms enables us to design systems that have a certain level of robustness, such as airplane. For example, airplane is a system that is designed to achieve stable flight against taburance of atmospheric conditions and possible damages of airplane subsystems. A flight control system can continue to maintain its ability to control flaps and ladders even if one of four hyduralic systems is damaged. This is possible because hyduralic systems are built redundant. Automatic flight control enables stable flight against various atmospheric perturbations due to its feedback control. In addition, it is composed of three independent flight control computers. Three computers are developed to attain identical functions (homogeneous redundancy), but designed as differently as possible (heterogeneous redundancy) to avoid common mode failure. The use of digital system decouples functional signal layer from the low level voltage fluctuation. (Fig. 3)

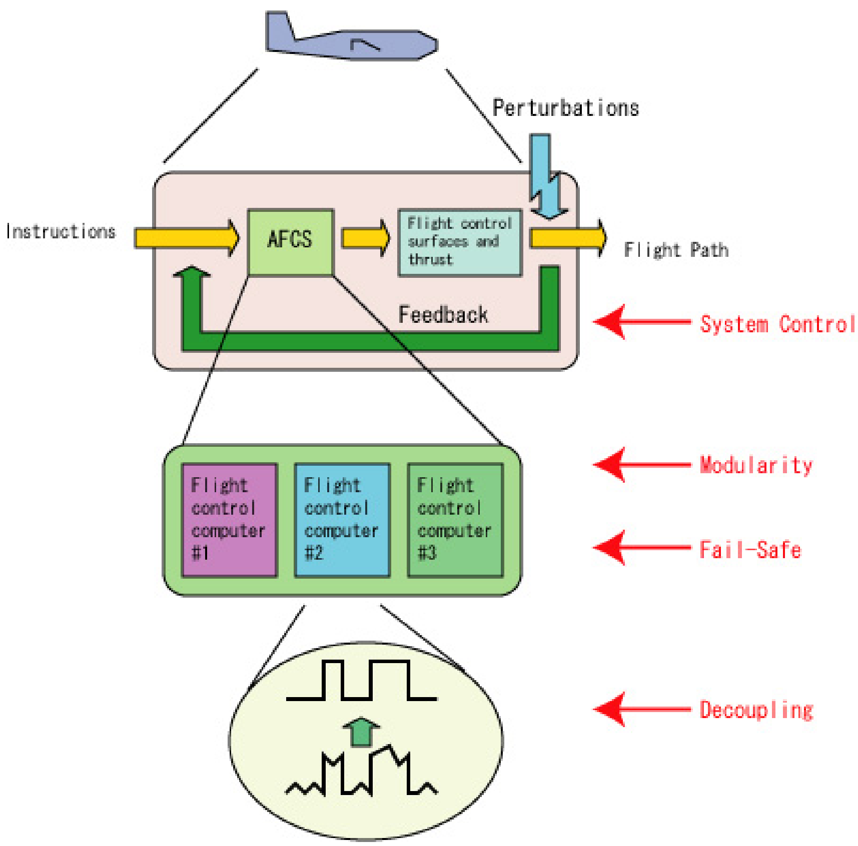


Fig 3: Airplane as an example of engineered robust system

In principle, robustness of the system can be enhanced by designing the system, composed of modular elements, to have redundancy in various aspects and impose appropriate feedback control.

However, simply combining basic mechanisms does not archive robustness for broader range of perturbations. Airplane assumes most sensory readings are correct and sufficient for autopilot. It is effective only under specific assumption where input information channel can be pre-defined and systematically integrated. The architecture for integrating information has to be defined for building truly robust system.

3.2 Global Network Architecture

The Bow-Tie architecture was recently proposed as a global network structure found in internet and biological systems. It consists of variety of inputs, a conserved core network, output networks, and control loops spanning within and between each sub-network. (Fig 4)

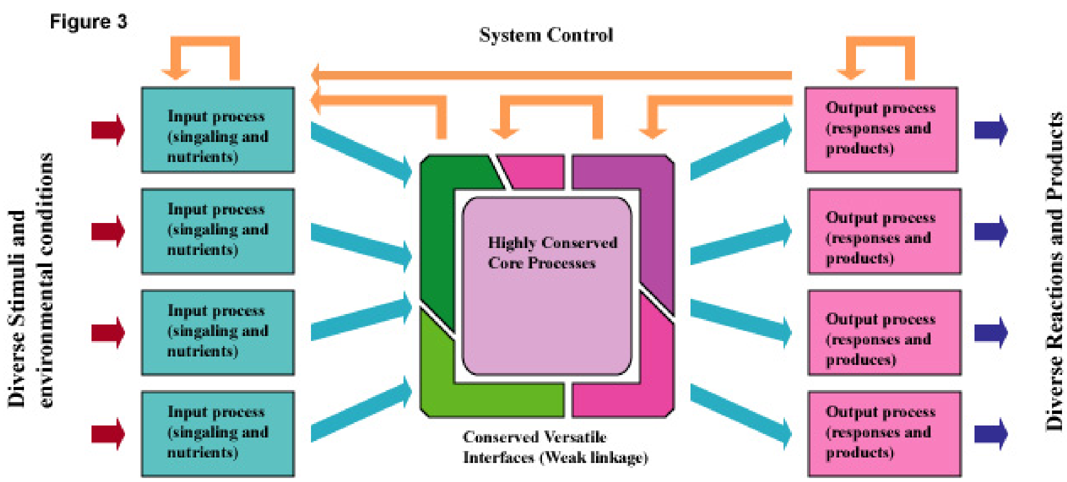


Fig 4: The bow-tie architecture

We have investigated actual biological networks on signal transduction where diverse input stimuli are transmitted into nucleus and trigger various cellular responses. Comprehensive maps of EGFR signalling network and TLR networks are created for the first time [Oda et al., 2005; Oda and Kitano, 2006]. The structure analysis of the network revealed that the bow-tie structure is consistent framework for network involved in biological signal integration. Diverse inputs are once converged into smaller numbers of components in the middle layer, then relayed to output after a certain processing. With this architecture, it is expected that the middle layer may have a certain abstraction and classification function that have emerged through evolution (Fig 5). This resembles the three-layer neural networks with limited hidden layer for generalization capability.

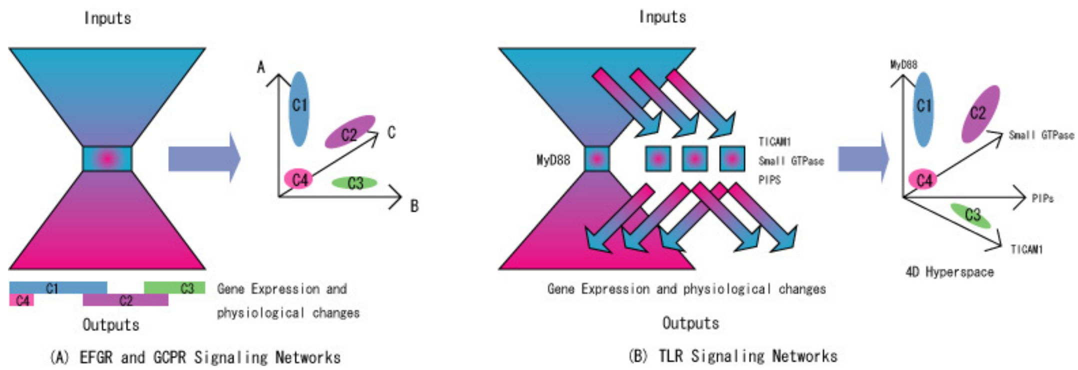


Fig 5: The Classifier Hyperspace in biological signalling systems

4. Implications for Robust Engineering Systems

These findings, along with other findings not listed above, has interesting implication for designing of engineering systems that are robust against dynamic change of environment. The central issue is to consider "robustness" as the central feature of engineering system design that reflects global architecture and basic mechanisms described.

4.1 The Bow-tie Architecture for Autonomous Intelligent Systems

While information fusion has been discussed in various aspects in the past, the issue has not been settled on at which layer the information shall be fused and what is suitable architecture for information fusion. Some argued for low-level, at pixel and sensory readout level [Ikeda et al., 2003], whereas other argues for fusion at concept formation level at symbolic layer [Brachman, et al., 1985]. Architectures of biological networks indicate that bow-tie structure has been evolved through long history of evolution for information fusion in biological systems with only a handful of variation at the global level. For relatively well-defined set of stimuli, a bow-tie structure that has limited intermediate nodes can be very effective and such layer shall be evolved or adapted for generalization and concept formation through stimuli exposed. In the relatively new and highly diverse stimuli, specific modification to downstream of bow-tie seems to be the proper architecture as abstractions may not sufficiently evolved or requires more precise control based on different stimuli. It is yet to shown theoretically how these two types of global architecture may affect generalization and specific behavioural control of the system.

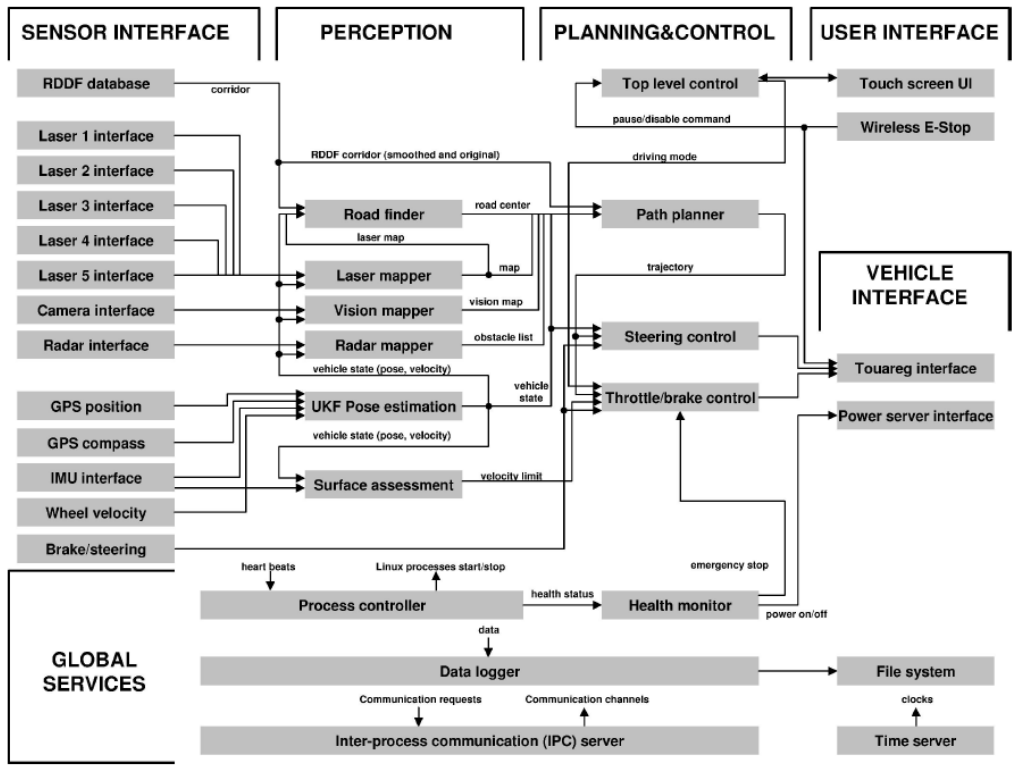


Fig 6: System Architecture for Stanly, a winning autonomous system for DARPA Grand Challenge

It is interesting to note that system architecture of STANLY, a winning autonomous vehicle for DARPA Grand Challenge, resembles a partial bow-tie structure where diverse inputs converge into smaller numbers of modules that ultimately control throttle and steering (Fig. 6)[Thrun, et al., 2006]. While such architecture is inevitable when only two degree of freedom exists for control, it is the first step toward more complex systems that can operate under different context. In the Stanly architecture, output network do not exists in reality as possible behavioural patterns and context is limited. However, if the system must operate in more complex environment with higher degree of freedom for control as well as required to perform in multiple contexts, the system must incorporate mechanisms for coordinating different type of behaviours.

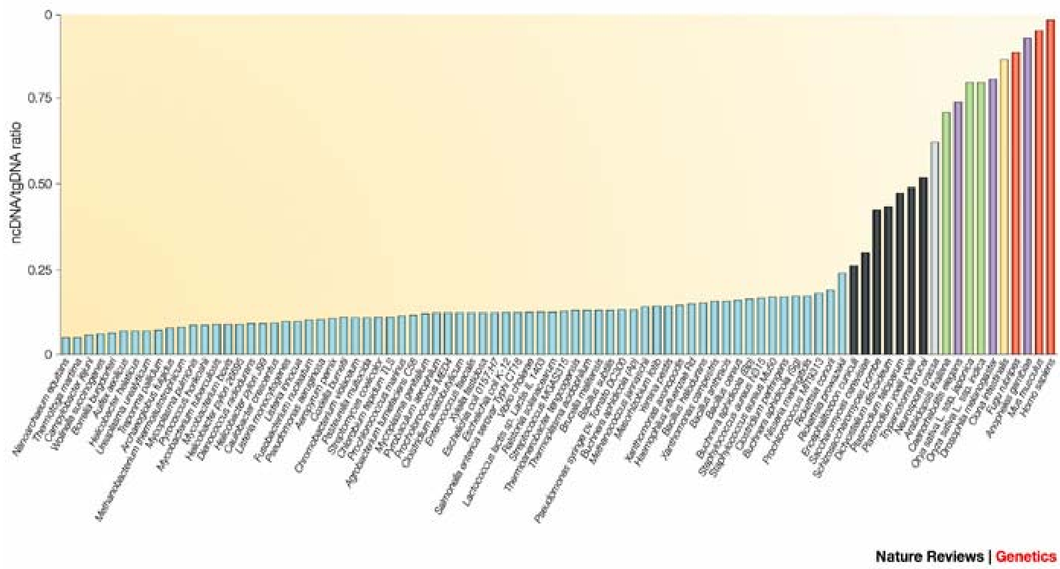
Nevertheless, there are numbers of features present in biological system are yet to be implemented in engineering system. Although not all of them are suitable for artificial system, there are numbers of control architecture that are worth considering. Some of the work performance under the grand proposes possible bow-tie architecture and multi modal sensory systems [Kitano, 2004b; Kitano et al., 2004].

4.2 Layered Control, Context-Switching, and Evolution of Regulatory Control

Cells operate in both dynamically changing environments as well as in rather stationary environment. During the developmental stage, cell has to operate in radically different environment and cell itself will undergo differentiation to make major switch in their control mechanism and adapt to new operating context. The differentiation often took place with chromatin structure modifications in which numbers of genes are affected. Chromatin structure change is true program of the cell where expression of genes may be considered as microcode. Hierarchical organization of program execution in the context-dependent manner is one of mechanism that can robustly cope with perturbations in different context. One the other hand, bacteria generally does not perform differentiation, and does not seem to have major chromatin remodelling activity. It is insightful that context-switch mechanism has been evolved in rather explicit manner in multi-cellular organisms, but not in other organisms.

Multiple layers of control are yet another feature that are typical in biological systems but not clearly observed in most engineered system. Control of engineered systems tends to be mono-layer due to transparencies of design. Regulation of cellular activities are modulated by protein-protein interaction, ion channel, and other reactions with relatively fast temporal window, transcriptional and translation regulation that has longer temporal window, and chromatin remodelling that act as contextual switch of overall genetic program. In addition, significant RNA regulation has been found in recent days. This is a striking discovery where chromosome regions mostly considered as "junk" seems to function to regulate cellular behaviour as noncoding RNA (ncRNA), RNA that does not encode protein structure information [FANTOM3, 2005]. Looking at the evolution of organisms, it is interesting to note that components involved in cellular regulatory mechanism is increasing at accelerated speed, much faster than the speed of genome size increase. This obviously means biological system with higher-level of complexity are required to have extensive and multilayered control mechanisms. In fact, it may be the case, what may limit the evolution of organisms in terms of complexity is difficulty to accommodate more sophisticated control. ncRNA is rarely observed in simple organisms, and yeast is the simplest eukaryotic cell that staert to have ncRNA based regulation. In mammalian, it was found that most transcripts are ncRNA. The ratio of ncRNA increases as complexity of organism increase. It is yet to be determined how ncRNA contribute to robustness of cellular system, particularly in integrating information and ensure robust response of the cell. However, discovery in this aspect of cellular regulation may provide us novel insight on how complex regulation have evolved in biological systems, and how to re-implement such scheme in engineered system that will be increasingly complex in future.

Implications and how to implement this context switch and evolution of layers of regulatory control in engineering systems is yet to be found, however, the work performed in the project have identified that this is potentially an important technical feature to build truly autonomous systems.



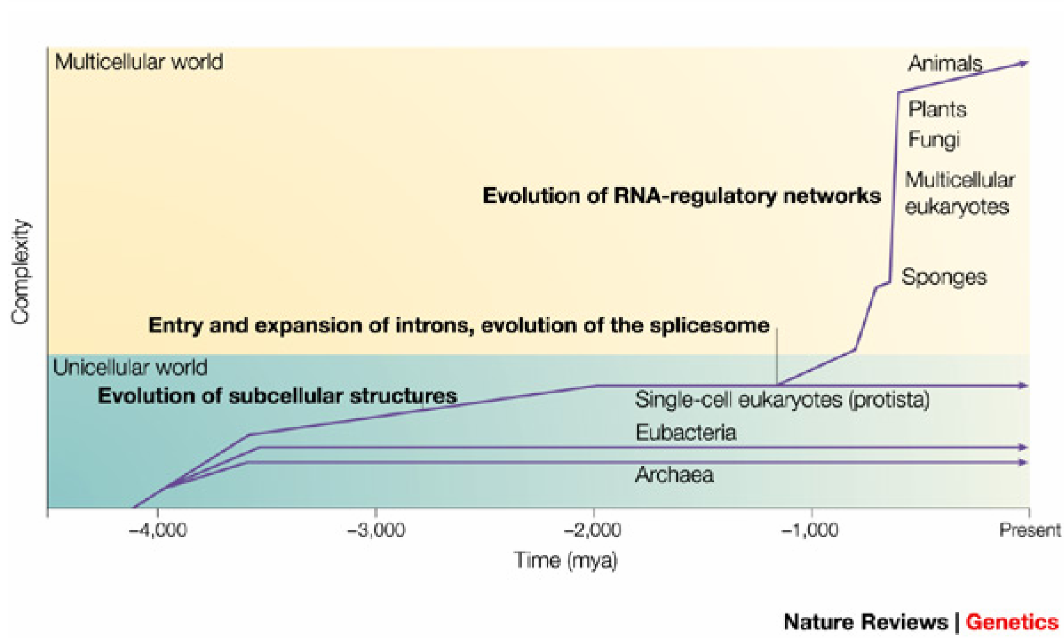


Fig 7: Evolution of regulatory control in biological systems

***(Mattick,* RNA REGULATION: A NEW GENETICS? *Nature Reviews Genetics* 5, 316-323 (2004); doi:10.1038/nrg1321)**

4. 3 Robustness Trade-offs

Trade-offs inherent in evolvable robust system is critical feature of the system. Our investigation on cancer, diabetes, autoimmune disorders and cellular mechanisms all revealed that such trade-offs are ubiquitous and inherent properties of robust evolvable systems. Carlson and Doyle pointed out that robustness may be a conserved value and has robust yet fragile property is inherent in any system. This is very important feature that has to be considered in designing engineered system. Studies revealed that trade-off does not only exist between robustness and fragility, but also between resource demands and performance. Thus, robustness, fragility, resource demands, and performance may be equated in a set of equation. This implies the system designer has to define which region of parameter the one should aim at in designing the system.

The system that has high level of resolution requires extensive computing power to process, and could be fragile against certain type of faults. Information fusion, if effectively designed, may compensate for fragility of such high performance system by providing alternative sensory channel. Of course, this will add up the cost and may sacrifice overall performance of the system by adding weights if mobile robot is assumed. These trade-offs are relevant to information fusion and integrated autonomous systems that has to operate in open, dynamic, and uncertain environment.

5. Conclusion

With the increasing complexity and tendency for network-based distributed systems, artificial systems are getting closer to biological systems. Thus, investigation of robustness, information fusion, behavioural control, and evolution of biological systems shall provide us with rich insights for future design paradigm of distributed, networked, and autonomous engineering system. In the distant future, the author believes that sufficiently complex engineering systems share substantial architectural similarities with biological systems. Lessen shall be learned now from 40 billion years of design challenges through the evolution.

The work performed in this research program initially investigated possible architecture and approach for information fusion within traditional paradigms. However, it became apparent very quickly that none of traditional paradigm actually fits to overcome inherent difficulties facing environments that are dynamic and uncertain. Thus, aside from engineering work on sensory and robotics systems as well as rescue agent simulation system that are not mentioned here, we have extended our scope to learn from biological systems that have actually survived and evolved under dynamics and uncertain environment. Some of insights has been discussed in this executive summary, and there are numerous findings that will be documented in future as results of this research program.

References

[Brachman et al., 1985] R.J. Brachman, V.P. Gilbert, H.J. Levesque ; An Essential Hybrid Reasoning System: Knowledge and Symbol Level Accounts of KRYPTON ; Proceedings of IJCAI 9, pp. 532-539, 1985

[Brooks, 1991] R.A. Brooks. Intelligence without Representation. Artificial Intelligence, Vol.47, 1991, pp.139-159

[FANTOM3, 2005] FANTOM3 Consortium, The transcriptional landscape of the mammalian genome.
Science. 2005 Sep 2;309(5740):1559-63

[Ikeda, et al., 2003] T. Ikeda, H. Ishiguro, and M. Asada, Adaptive Fusion of Sensor Signals based on Mutual Information Maximization,IEEE International Conference on Robotics and Automation (ICRA), pp.4398-4402, Sep. 2003

[Kitano, et al., 1993] Hiroaki Kitano et al. Grand challenge AI applications. In Proceedings of the Thirteenth International Joint Conference on Artificial Intelligence, pages 1677--1683. Morgan Kaufmann, 1993.

[Kitano, 2004a] Kitano, H.. Biological Robustness. Nature Review Genetics. 5, 826-837, 2004

[Kitano, 2004b] Kitano, H., Challenges in Robust Situation Recognition through Information Fusion for Mission Criticial Multi-Agent Systems, Proceeding of RoboCup-2003, Springer-Verlag, 2004.

[Kitano, et al., 2004] Kitano, H., Kaminaga, H., and Landerman, J., Robust Architecture for dynamical environments, FUSION 2004, 2004.

[Mattick, 2004] Mattick,J., RNA REGULATION: A NEW GENETICS? Nature Reviews Genetics 5, 316-323 (2004)

[Nakadai, et al., 2000] Nakadai, K.; Lourens, T.; Okuno, H.G.; Kitano, H. Active audition for humanoid. 7th National Conference on Artificial Intelligence (AAAI-2000), Austin, Aug. 2000, 832-839

[Nakagawa, et al., 1999] Nakagawa, Y.; Okuno, H.G.; Kitano, H. Using vision to improve sound source separation. 16th National Conference on Artificial Intelligence (AAAI'99), Orlando, July 1999, 768-775

[Oda et al., 2005] Oda, K.; Matsuoka, Y.; Funahashi, A.; Kitano, H.; A comprehensive pathway map of epidermal growth factor receptor signaling. Molecular Systems Biology. 2005

[Oda and Kitano, 2006] Oda.K; Kitano, H.; "A comprehensive map of the toll-like receptor signaling network", Mol Syst Biol : msb4100057. Apr. 18, 2006

[Okuno, et al., 2004] Hiroshi G. Okuno, Kazuhiro Nakadai and Hiroaki Kitano: Effects of Increasing Modalities in Recognizing Three Simultaneous Speeches, Speech Communication, Vol.43, No.4, pp.347-359, 2004

[Thrun et al., 2006] Thrun, S and M. Montemerlo and H. Dahlkamp and D. Stavens and A. Aron and J. Diebel and P. Fong and J. Gale and M. Halpenny and G. Hoffmann and K. Lau and C. Oakley and M. Palatucci and V. Pratt and P. Stang and S. Strohband and C. Dupont and L.-E. Jendrossek and C. Koelen and C. Markey and C. Rummel and J. van Niekerk and E. Jensen and P. Alessandrini and G. Bradski and B. Davies and S. Ettinger and A. Kaehler and A. Nefian and P. Mahoney, Winning the DARPA Grand Challenge, Journal of field Robotics, Accepted.

Chapter 1: The Architecture for Robust Systems

1.1 Robust Architecture for Dynamical Environments

Abstract – *The fundamental requirements of rescue systems are robustness against perturbation imposed by disaster and practical design for production and deployments. Information fusion at various levels needs to be designed to be robust and scalable to size and types of disasters. This paper discusses basic framework of the system that is designed to cope with individual and home securities, but can be converted into a part of large system in case of large scale disasters. It follows notion of robustness that are found in many engineering and biological systems, and explicitly use such concept for basic design.*

1 Introduction

The application of information technology to rescue human life in disaster is one of the major challenges in IT-related research with high impact to the society. Such system has to be robust against range of disasters, but also has to be cost effective and easy to maintain in order to be practical.

1.1 Scalability is an economical and sociological requirement

When considering disaster rescue systems, we tend to assume large scale disasters, such as earth quakes hit Kobe, Taiwan, Turkey, and Iran. However, for each specific area to suffer disaster of this magnitude is rare. In some cases, it happens only once in few centuries.
For rescue systems to be practically deployed and maintained, as well as being economically justifiable, it has to be able to cope with smaller incidences that occur in daily life.

It has been shown that size of earth quake and its frequency has specific correlation that follows the power law. The power law distribution is observed in broad range of phenomena. It would be reasonable to assume that scale and frequency of general disasters and crimes also follows the power law.
This implies that the system can also be used for small incidences can save substantial numbers of people aside major disasters. In addition, because the system will be maintained in daily basis, the system is more like to be functional in case of major disaster.

In addition, this mitigates one of the major issue in victim search for the large scale disaster rescue that is how to get sensors near the victims, when location of victims is not known and the environment is extremely hostile. Once such a system is widely accepted and used in the daily life, very large numbers of sensory devices are readily deployed to each individual and to each house.

The design of the system has to be scalable, or scale free, in the sense the system deployed for personal use can be also an integral part of community wide, or even nation wide system.

The system need to be scalable in three aspects;

(1) Problem scalable is a capability of the system to cope with different types of incidences,
(2) Size scalable is a system's ability to cope with incidences with different magnitudes, and
(3) Generation scalable that ensures the system to be continuously up-graded without reinstalling the entire system.

Particularly, the requirement for problem scalability where the system to cope with various incidences including attack on individual working on the street, someone breaking into the house, fire, a major earth quake, and large scale terrorist attacks. Due to the infrequencies of the major disasters, the system will be economically feasible and sociologically acceptable only when it can be used for incidents in everyday life. This enables modules to be manufactured at large quantity, so that cost can be drastically reduced.

Size scalability requirements indicates the need for standard architecture and protocols that enables such modules connected to form network of systems, regardless of manifacturers and original configurations.

Generation scalability can be attained also by assuming stable standard architecture and protocols, so that modules with new technologies can be added by comply with the standard and protocols, as well as adding consistent additional protocols with backward compatibilities.

1.2 Robustness as fundamental architectural principle

Since the system will be used under hostile and uncertain environments, robustness shall be the major concern in the architectural design of the system. Consideration shall be given at all levels of system to enhance its robustness.

Robustness is a property of the system that can maintain certain properties against certain perturbations. The system generally exhibits adaptation against changing environments and insensitivity to parametric changes. Such properties can be achieved by few basic mechanisms that are; (1) feedback control, (2) redundancy, (3) modularity, and (4) structural stability [1, 2].

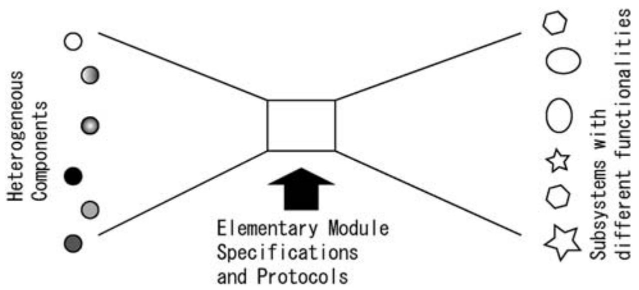
For example, airplane is a system that is designed to achieve stable flight against taburance of atomospheric conditions and possible damages of airplane subsystems. A flight control system can continue to maintain its ability to control flaps and ladders even if one of four hyduralic systems is damaged. This is possible because hyduralic systems are built redundant. Automatic flight control enable stable flight against various atomospheric perturbations due to its feedback control. In addition, it is composed of three independent flight control computers. Three computers are developed to attain identical functions (homogeneous redundancy), but designed as differently as possible (heterogeneous redundancy) to avoid common mode failure.

In principle, robustness of the system can be enhanced by designing the system, composed of modular elements, to have redundancy in various aspects and impose appropriate feedback control.

In the context of this research, the system must ensure robust detection of anomalies and transmission of information on theater of disaster under various types of disruptions.

2 Universal Security Architecture

Requirements on scalability and robustness constraint possible design space for architecture of general security systems. Naturally, it will be consists of well defined and low cost multifunctional sensory modules with reconfigurable communication capability. There should be limited types of such modules forming building blocks of the system. There should be defined protocol that enables standard command, communication, and control of modules.
Each module shall meet defined functionalities, but designed differently, so that heterogeneous redundnacy can be maintained.
Combination of modules enables various functions to cope with range of incidences that ensures scalability regarding its problem and size.
This fundermental architecture can be illustrated as bow-tie architeture, that is claimed to be the fundermenal architecture of robust systems (Fig. 1).



Figrue 1: The bow-tie architecture of robust systems

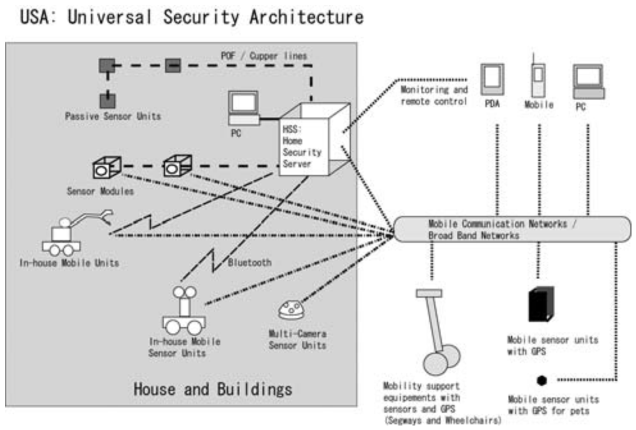


Figure 2: An example implementation of the system

Figure 2 illustrate an example of how such systems can be implemented for individual use. Numbers of sensor modules are distributed with fixed and mobile platform that are accessed through home security server or directly through mobile communication networks. Each module can be function as probes for sensing victims in case of large scale disaster.

3 Module Design

3.1 Module Functionalities

The basic element of the system is a multi-functional sensory module that is small and versatile. The module is designed to be robust in sensing its own environment and communicating with other modules. While there are several types of basic modules, an example of basic feature is as follows:

(1) Sensors: CCD or CMOS image sensors, Infra-red, tactile, microphone
(2) GPS and Gyro
(3) Speakers
(4) Lights
(5) Wired, Wireless, and IR communication channels
(6) Battery opertion capability (includnig additional solar panels)

Sensors can detect situations around the module. GPS and gyro can identify location and posture of the module. Speakers can be used to (1) call victims asking for their reply, (2) communicate with victims once found, (3) communicate with other modules using a low-speed communication protocol, and (4) to notify other modules and human rescue staff where the module located. Lights are used to (1) to probe dark confined envrionment by imaging devices, (2) communicate with other modules, and (3) indicate location of the module to other modules and human rescue staff. Various broadband and narrow band communication channels are mostly used for daily life or home and indiviudal security purposes, but can be used in large disasters if such infrastructures are still available. Since we cannot assume electricity in major disaster stiuation, modules should be operational with battery.

Such versatile module can be placed in house or mounted on mobile platforms, such as robots or automobile.

3.2 Robsutness

Robust sensing is attained by; (1) the use of multiple sensor units, (2) the use of multiple modalities of sensing, and (3) adaptive control of sensory units.

3.2.1 Redundancy

The module is equipped with sensors for different type of signals, such as CCD or C-MOS image devices for normal visual spectrum, infrared sensors, microphone, tactile sensors, etc. This ensures robustness through heterogeneous redundancy in sensing environment under possible perturbations, such as undesired lighting that disable normal vision sensors.

Each sensory module is expected to have multiple units within a module, so that damage on one of the sensors do not directly leads to total dysfunction of the system. At the same time, the use of multiple modules for proximal area would add robustness as a whole system.

We have designed and developed small sensory modules that has multiple imaging devices to cover broad range of visual field (Figure 3).

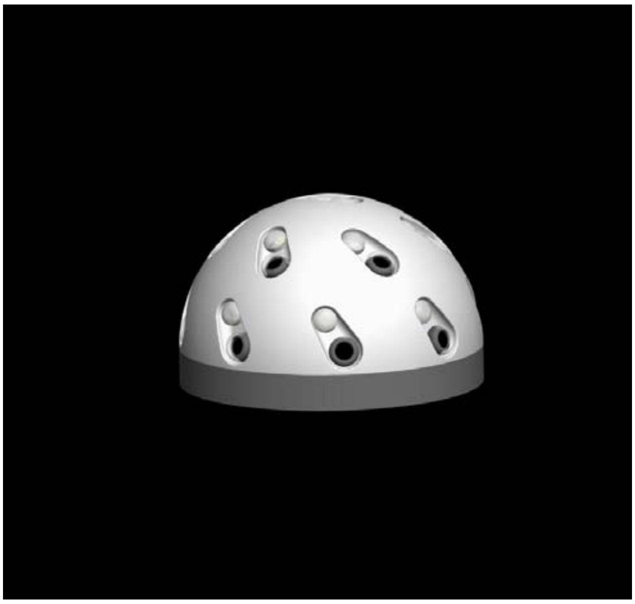


Figure 3: Prototype of sensory module

3.2.2 Adaptation

Adaptation against environmental stimuli can be accomplished by (1) actively moving sensory device, and (2) changing the amplification gain.

Identification of the direction of sound source is one of the features that is highly useful in locating victim location. However, due to physical property of sound, directional resolution is maximized when microphone is aligned tangential to the sound source. Thus, active audition system has been developed that can react to possible sound source direction, and turn microphone units to maximize directional resolution [3-5]. This can be considered as extension of animated vision and active vision concept to audition [6].

Bacteria exhibits high level of robustness in chemotaxis [7]. With gradient chemoattractant environment, bacteria swim toward high concentration area, and such a behavior is maintained for broad range of concentration level. It is attained by the use of integral feedback involving the receptor complex, fragella motors, and intermediate enzymes (Figure 4) [8]. This feedback system react to changes in the concentration of chemoattractant, instead of absolute concentration level. When concentration level of chemoattractant changes, receptor activity rate changes that triggers change in fragella motor activity. However, feedback control acts to bring activity level of this module to the steady state. Because of this, bacteria can react to further stimuli. Such adaptation against external stimuli is ubiquitously observed in bioloigcal signal transduction.

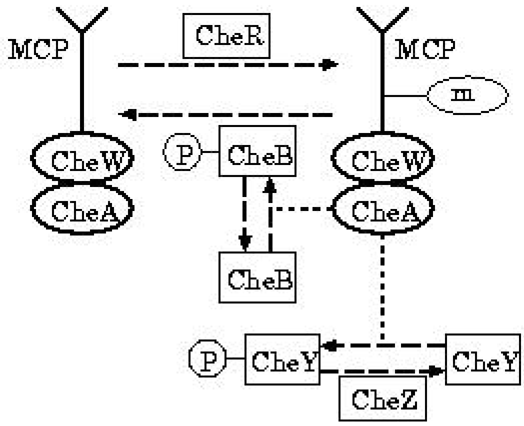


Figure 4: Feedback control in bacteria chemotaxis

Similar principle can be applied to sensory systems. First, dynamics range of device can be augmented by implmenting a feedback control to adjust signal intensity that reach sensing device. Auto-iris is one of such feedback systems that are implemented on engineering systems. Microphone dynamics range can be augmented by creating physical devices that can adjust sound level reaching the microphone. Second, gain adjustment of the amplifier connected to the sensing device provides stable signal coping with changes in the incoming signals.

In addition to such signal level adaptation, anomaly detection requires distinction between normal envrionment with certain fluctuation and anomaly. Fro example, if sun lights into the room gradually changes over time, it is normal due to movement of the sun. However, if it changed drastically within a few seconds, it may due to someone manipulated room environment which is a potential anomaly. Integral feedback as seen in bacteria can cope with such changes, but additional mechanisms need to be implemented to avoid false positive that such manipulaiton is done by the family members. Some securty key need to be implemented that supercedes automatic anomaly detection.

3.3 Information Fusion

Automatic detection of anomalies and sending the message, as well as recording the data, is one of the major functions that are expected in daily use of such devices.

Aan extreme AI solution is that each module to have intelligence program that can distingush anomalies and normal perturbations and send warning only when anomaly take place. However, this is not practical as false positive can not be eliminated if the system is tuned to detect all anomalies.

Practical solution would be to combine the system with physical and electric security keys, as well as pre-designed sensor neworks. Security keys can override anomaly detection function of the module, so that actions taken with securty key activated will not be detected as anomaly. At the same time, convnetional home security systems places infrared and open-close switches to doors and windows, so that movement of objects, doors, and windonws can be detected. Users can define the mode of operation, so that the system know which sensors has to be activated. Such conventional, and somewhat low-tech solution is quite effective.

Then, where is need for intelligence systems? Although most low tech systems can detect anomalies if it is well placed, it can not provide images of detailed situaiton and send such information effectively to users. Usrs are most likely to be in the situation access to the visual information is restricted or can use only limited size of screen such as mobile phone. In such cases, looking at images of numbers of devices are time consuming, and may not be able to find anomalies, even if it is reported and captured in one of the image sensors.
Intelligent information fusion would assists such situation by providing images that are scored highly suspicious to the user when the user first logged in to the system.
Also, it may able to tracking the movement of suspicious objects in the house.
Information fusion plays a critical role. Vision is often occruded and may not be able to cover an entire area. Autditory systems, on the other hand, may be able to detect sounds even if objects are occruded visually. With certain levels of direction identification capability, it may be able to located where the suspects may be hiding in the house.
In addition, using both visual and auditory information is shown to reduce false positives [9].

The other possiblity is the linkage with early warning system for earth quake. Using the time of earth quake vibration to propagate, the system has been already implemented in Japan that can send warning such as " an earth quake with intensity 5 to arrive 8 seconds from now". If such signal can be transmitted in machine readable form, modules can be immidiately activated to record situation before the arrival of the earth quake, and record how damages are inflicted. Such information would be enormous help to rescue teams, as they can understand who may be around and how collapse took place.

4 Robust Communication among Modules

Modules need to self-organize their network, so that information of the environment of each module can be transmitted to outside of the area, so that rescue teams can understand the situation, and act accordingly.

4.1 Redundancy

Each module have different communication modalities, including wired eithernet, wireless LAN or mobile phone, infra-red, sound, and light. Basically, each channels use same protocol, but modified according to band width of each modality. Communication channels are made redundant in a sense all these channels can communicate to other modules in normal condition. At the same time, it is heterogeneous because different mode of communication are selected to add robustness against unpredictable situations.

After the initial shock, surviving modules start to establish network of communication. Ech channels are tried to estblish connections. When wired ether net is tried but failed, then wireless LAN or mobile phone channel is tried. When it failed, use light or IR channel to communicate with nearest modules.

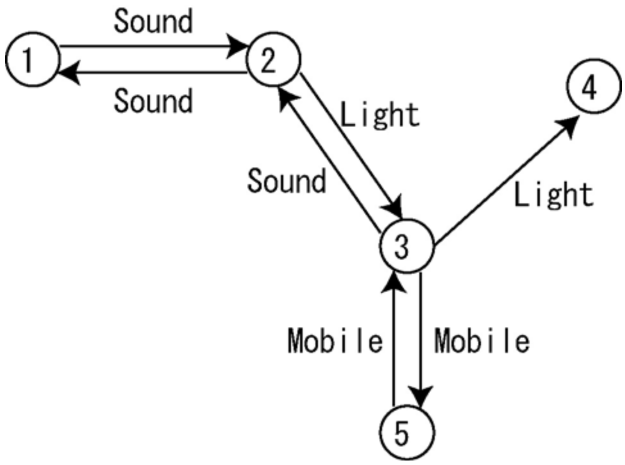


Figure 5: Emergent network based on survived modules

Figure 5 illustrates possible configuration of the network. Module 1 and 2 are visually partitioned, so that only sound can be used to communicate between these modules. Module 2 can send signals to module 3 usnig lights, but module 3 can not send sufficient lights to module 2, so that sound channel is used instead. Module 3 can communicate with module 5 thrhough mobile communication channel. It is most likely that this module to be the gatewya to larger networks. Module 3 can send signal to module 4 via light, but module 4 can not communicate with any other modules.

The communication program on the module has to be flexible to allow such heterogeneous network with different physical properties and band-width.

Ideally, triangulation shall be done using sensros and GPS and gyro, so that physical configuration can be estimated.

4.2 Adaptation

The problem is how to spontaneously organize the network topology with heterogeneous modalities and often interrupting channels.

An interesting observation has been shown that in the small world network, any two node can be communicated within small numbers of hops, such as 6 or 7 hops. This can be attained by growing the network accodring to preferential attachment principle. The priferential attachment means that node with highly connected with other nodes are more likely to have extra connections, so that it spontaneously creates hubs in the network. The advantage of such network is that it is robust against random failure of nodes. In this context, robustness is measured by the stability of the average number of hops between arbitrary chosen two nodes in the network.

This is desirable property for nework connecting sensory modules for victim search, because communication network topologies can not be determined in advance and an be interupted by failure of any of nodes in the network.

5. Active network reconstruction by mobile modules

After the reconstruction of networks by stationary modules, the mobile systems may be activated to cover the areas that are not covered by the stationary modules. This requires certain level of identification can be made on the location of each modules and networks. Then, the task is to deploy mobile modules where such networks are not established, or the grain size to cover the area is not sufficient.

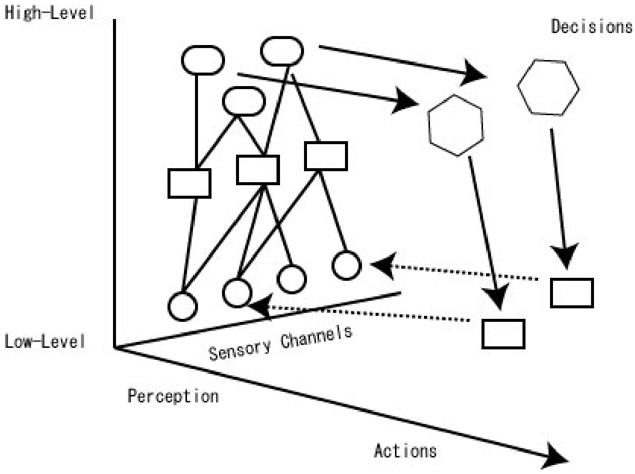


Figure 6: Feedback loop of information fusion and actions

Decision on how to deploy mobile modules may be under the closed loop of low-level sensory fusion, high-level information fusion, and decisions followed (Figure 6) [10].

6 Adaptive airborne deployments for spatial information fusion

Given the spatially distributed and scattered nature of initial networks, theater scale deployments of airborne modules to efficiently fill the gap would be effective.
The author has previously proposed airborne deployments of sensor modules where no sensors are available on the ground [10]. The scenario in this paper is that there are fragmented networks of modules are available on the ground, but scattered and global triangulation is not completed.

In this case, adaptive formation of modules are modified to focus on the area ground based modules are not clustered, and small triangulated modules are diverted into the fragmented network to identify spatial location as well as to ensure its connection to global network to be establish after the arrival of the airborne modules (Figure 7).

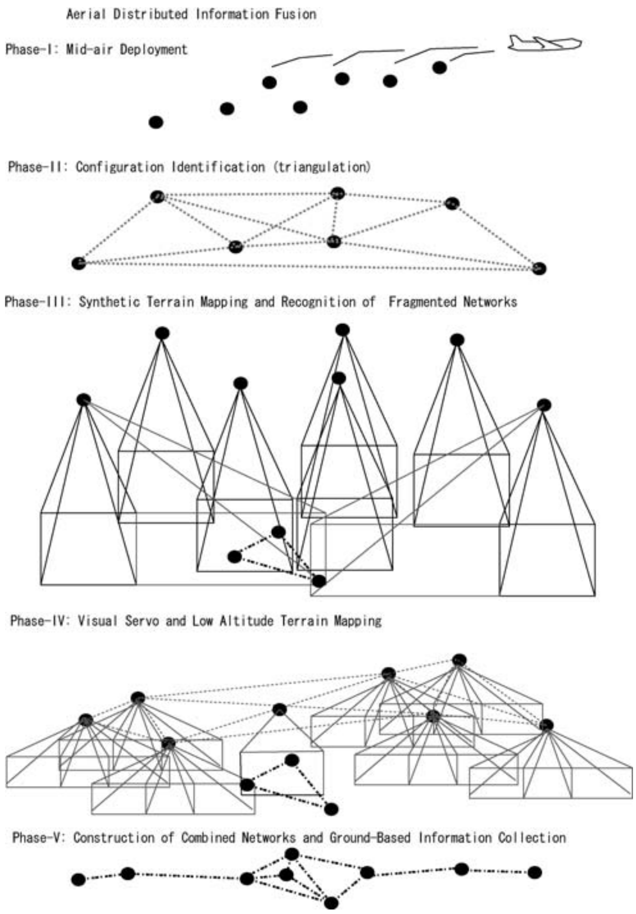


Figure 7: Airborne deployment of modules for aerial terrain mapping and network reconstruction

7 Conclusions

In this paper, basic design strategies for disaster rescue systems have been discussed. The fundamental principle behind the design is scalability and robustness. For such a system to be practical and acceptable, it must be able to cope with incidents in the daily life, in addition to rare events of large scale disasters. This is the only way to make systems affordable, deployable, and maintainable. Redundancy in sensory systems and feedback control shall provide robust perception and detection of anomalies. Emergent network of communication enable the modules to communicate and transmit information to rescue teams, as well as sending messages of rescue teams to victims in debris. Active probing using ground based mobile modules as well as theater scale airborne deployment shall provide global network by connecting fragmented networks and enable us to understand pictures of the terrain globally.

It is important at this moment, overall framework of the system to be investigated and defined. Details of each technical aspect shall follow once overall architecture is defined as attempted in this paper.

1.2 Challenges in Robust Situation Recognition through Information Fusion for Mission Criticial Multi-Agent Systems

The goal of this paper is to highlights one of emergent scientific issues in RoboCup task domains that has broader applications even outside of the RoboCup task domains. This paper particularly focuses on robust recognition through information fusions issue among numbers of others issues that are equally important. The robust recognition through information fusion is selected because it is one of the most universal issues in AI and robotics, and particularly interesting for domains such as soccer and rescue that has high degree of dynamics and uncertainty, as well as being resource bounded. The author wish to provide a conceptual framework on robust perception from single agent to multi-agent teams.

Robustness and Information Fusion

The RoboCup project is an interesting research platform because it has multiple domains that have both difference and similarities in basic domain features. Soccer is a dynamic game with real-time collaboration within teammate, but adversarial against opponents. Major uncertainties are generated by (1) opponent strategies, (2) uncertain and stochastic nature of physics on ball movements and other factors that affect course of each action, and (3) uncertainty of real-time behaviors of each player. On the contrary, rescue domain is a dynamic and mission critical domain with high degree of uncertainty and partial information under hostile terrain that are totally different in each case. Major uncertainties are generated by (1) unknown terrain and victim information, (2) uncertain and stochastic nature of incoming information, success of each operations, numbers of external perturbations, and other social and political factors, and (3) limited information on individual victims and their situations.

It is interesting to note that despite differences in the task domain, there are substantial commonalities in structures of uncertainty. There are uncertainty and limited information at the macroscopic level at the level of entire terrain or theater of operation and at the microscopic level which is the scale of individual players or victims. In addition, there are issues of unknown and unpredictable perturbations throughout the operation.

In order to best accomplish the task, a team (or teams) of agents, either robotics or informational agents, need to be robust in perceptions and actions, as well as their team behaviors. It should be well coordinated to reconstruct a model of the terrain and other agents in the scene against various noise, uncertainty and perturbations, so that effective actions can be taken. A set of actions need to be robust so that failure of one or more of such actions do not leads to catastrophic failure of the overall mission.

Robustness of the system is generally exhibited as capability of the system to (1) adapt to environmental fluctuation, (2) insensitivity against fluctuations in system's internal parameters, and (3) graceful degradation of performance, as opposed to catastrophic failure of the system.

This applies from sensory level to higher multi-agent team level. A brief example at the team level shall make clear what does robustness means. For the soccer team, this means that the team should be able to cope with differences in strategy and physical performance of opponent team, not being seriously affected by changes in fatigue and other factors of players, and removal of one or more players does not results in complete loss of its team performance. For the rescue team, it means that the team can cope with various different disaster scenario and dynamical changes in the situation, ability of cope with unexpected fatigue, damage, and resource shortage, and capability to carry out missions even if some of its rescue teams have to be withdrawn from the scene. For the rescue team that has to cope with extremely hostile environment, robustness is one of the essential features of the system.

Robustness of the system is usually attained by (1) the use of proper control, such as negative feedback, (2) redundancy, or overlapping functions of multiple subsystems, (3) modular design, and (4) structural stability.

Extensive research has been made on properties of robustness in biological systems, and these traits were shown to be universal using numbers of examples, including bacteria chemotaxis, robustness of gene transcription against point mutations and noises, stable body segment formation, cell cycle and circadian period, etc.

Bacteria, for example, swim toward chemoattractants by sensing graduent of concentration. This capability is maintained regardless of concentration level, steepness of the gradient, and keep track of graduent changes consistently. Integral feedback has been identified as a key intrinsic mechanism in which bacterial behaviors are controlled by activation of receptor complex, but deactivated by a negative feedback loop with integral components. This feedback control enables behavior of bacteria dependent on the level of concentration changes took place, but independent of absolute concentration level of chemical in environment. Similar mechanisms are observed widely amoung different speceies. Feedback control is only one of several mechanisms behind biological robustness.

On the contrary, artificial systems tend to be less robust, and reply on rigid build-in design that may easily fail under fluctuations. How to build robust systems from sensory-level to strategy-level in a consistent manner is one of the major issues in RoboCup research.

In the rest of the paper, possible research directions for robust systems particularly focusing on information fusion aspects are discussed. Information fusion is raised here because it is relatively universal in different domains, and critical for strategic actions to follow. Issues of robust strategic decisions and executions will be the other robustness issues in multi-agent teams, but will not be discussed due to space limitations.

Dimensions of information fusion for robust systems

Information fusion for robust systems has to be considered for multiple aspects:

* **Abstraction**: An interactive processing of different abstraction levels, such as interactive processing of low-level sensory information and high-level recognition and strategy, enhances robustness by providing interlocking feedback of information thereby hypotheses may converge to more plausible one.
* **Multiple Sensory Channels**: Integration of multiple modal perception channels can contribute to improve robust perception by complementing missing information by perception channels with different characteristics.
* **Perception-Action Loop**: Active involvement of probing actions into perception, that is an integration of perception-action loop to enhance recognition by actively manipulating the environment so that ambiguity can be resolved.

* **Spatio-Temporal Distribution**: Integration of spatio-temporally distributed sensory information, as well as absteacted symbolic information is essential to create overall picture of the situation, thereby robust adaptation to the situation can be done with overall re-evaluation of the situation.

Information fusion in these aspects contributes robust perception of theater of operation through one or more of four mechanisms of robustness.

Interaction of low-level and high-level perception and actions

Given the multi-scale nature of the domain that requires identification of situation at both macroscopic and microscopic levels, distributed and coordinated information fusion need to be performed that are ultimately combined to create a coherent model. Information fusion at the macroscopic level is called the high level information fusion (HiLIF) and that of the microscopic level is called sensory level information fusion (SLIF).

In the sequential model of AI, a famous Sense Model Plan Act cycle (SMPA cycle) has been used. This paradigm has been criticized as not being able to respond to environment in real-time, and an alternative approach named "behavioral-based approach" has been proposed.
While the behavior-based AI demonstrated effectively how simple robotics systems and virtual agents can behave in the real world without creating an internal model, it never scaled to perform complex tasks. In both soccer and disaster rescue, coupling of hierarchy of sensing and actions from low-level sensory units to high-level strategy generators is essential. Reactive control of leg movement to kick a ball must be coordinated with strategic choice of attacking patterns and a pass trajectory to enable such a strategy. Similarly, local actions and decision for the recovery of some critical life-lines has to be carefully coordinated with overall strategy.
In this context, low-level perception and action module is not merely behavior-based module. It must be able to recognize local situation that can be aggrigated at a higher level. SLIF should have a certain level of internal model.

While these examples are how overall strategy may constrain local actions, there are cases local actions influence overall strategy. Basically, it is interaction of bottom-up and to-down processes in which the architecture enabling it has been long standing theme in multi-agent systems. While this is well recognized issue, the author would not make further discussions than stating that RoboCup task domains, particularly humanoid league and rescue, are one of ideal platform for seriously tacking this problem.
This aspect of integration essentially exploits feedback control of the system for adaptation at certain abstract levels. Low-level perceptions and local decisions are aggrigated to higher-level that feedback differences between desired local situations and actions and actual situation and actions to reduce such descrepancies.

Information fusion of multiple sensory channels

Navigation, localization, and object identification of robotic agents tends to rely on visual information. While vision provides rich information, it is limited in several aspects. First, visual perception can be occluded by obstacles, including dust and smokes. Second, it has to have certain quality of light sources. These features impose serious limitations of visual perception for disaster rescue situation, because disaster scenes are generally highly unstructured, dusty, and may have

serious smokes from fire. Lights are often not available in confined environment where victims may be embedded.
Auditory perception, on the other hands, has different characteristics. It can transmit over obstacles, do not require light sources. In fact, various noises victims may make is a critically important signals for a victim location identification. Other sensory channels, such as odorant, CO2, and vibrations have different characteristics that complement each other.
Information of multiple modalities of perceptions may provide high level of robustness in perceiving the environment. Some of early efforts have been done using integration of auditory and visual perception.
Vision system often generates false positive identification of objects that is supposed to recognize due to similarity of color and shape in irrelevant objects. When the object is creating certain auditory signals, the use of auditory information to track the sound stream can effectively eliminates false positives. By the same token, objects could be occluded by obstacles so that vision system lost tracking, which can be compensated by keep tracking auditory signals if the object is making some sound streams. Early experiments indicate that well designed integration of multiple modal perception channels based on multiple sensory steam integration is effective for robust perception.
Now, the research topic shall be to create basic principle of robust object identification, tracking, and scene understanding by using multiple perception channels, most likely by defining a dynamical defined invariance that corresponds to each object as its signature.This approach is expected to attain robustness by exploring redundancy, or overlapping functions, of perception channels, so that degradation or failure of one perception channel is well compensated by other perception channels with overlapping functions.

Integrating actions to perception

It is important that the concept of active perception to be integrated into the system, so that ambiguities of information can be resolved by actively directing sensory devices and information gathering agents. Early research of this direction has been proposed as active vision and animated vision \cite{Ballard}, but it has to be extended to include not only vision and other perception channels, but also to more high level information collections. Conceptually, this is feedback control to minimize unknown, or ambiguous part of scene to zero.

In the resource constraint situation such as in disaster rescue, the concept of cost of active probing has to be introduced. Any action to obtain information is associated with cost, the use of resources, including time. Decision has to be made on whether actively probe new information or to proceed with ambiguities.

Suppose that a ball that is rolling from right to left is occluded by an opponent player, decision has to be made to use predictions of ball trajectory or actively probe the ball position. While actively proving the ball position may resolve ambiguity of information, it may loose time window to intercept the ball.
By the same token, in the disaster scenario, spreading of fire or cascading collapse of buildings may not be fully monitored by available sensors or information agents. A tactical decision has to be made to dispatch a unit to counter such incidence by predicting possible front of chain reactions or to mobilize information gathering agents to make sure the status of incidents. The cost of information gathering is the use of additional agents and time to wait until the situation to be disambiguated. On the contrary, a quick deployment of counteraction units runs a risk that the prediction is false and deployments are deemed ineffective. Always, there is a trade-off between cost of knowing and risk of not knowing. One of the research topics may be to find out principles of decision on cost of knowing versus risk of not knowing.

Spatio-temporal integration

Heuristics and knowledge-based estimation

Integration of spatio-temporal information is essential, particularly for disaster rescue operations. Theater of operation is widely distributed, and information is collected only at limited rate from limited locations. Basically it is a problem of making the best estimate of the situation by sparse sampling of complex terrain in 4-D (XYZ+T) space. Certain heuristics, such as continuity of the unfolding events, and a priori on structure of urban infrastructure are expected to be highly useful to constrain possible hypotheses. This applies to both low-level and high-level information fusion, but particularly useful for high-level information fusion where "fog of war" has to be resolved as soon as possible with limited resources. Advantage of this approach is that you can make reasoned estimate of the situation even for the area that cannot be directly measured. The drawback is that it requires substantial knowledge of the urban structures in usable form that are generally not available.

At the same time, how to increasing sampling points is the other big issue. One of the best ways is to make sure sensory systems are ubiquitously present in disaster scene. This can be achieve only by creating multi-functional systems that are useful in daily life, but can act as sensory units in emergency. Traffic signals and various monitoring cameras are possible resources that can cover public space. Home security systems, home entertainment robots, and a series of home electronic products are ideal for covering situations in each household. However, there are issues of securing telecommunication with such devices, as well as protection of privacy that are critical, but are outside of AI and robotics issues.

Adaptive airborne spatial information fusion

One of possible approach to solve this problem is to develop a small disposable sensory unit and deploy them in large numbers. Figure 2 illustrates one example of such systems which could be deployed airborne. The goal is quickly understand target terrain/city situation for the purpose of disaster rescue.

* Phase-I: Large number of small IF (information fusion) devices will be deployed mid-air
* Phase-II: Speed break is activated and speed is stabilized. Then each unit has some visual beacon or visual ID so that relation location of units can be determined by triangulation.
* Phase-III: First aerial photo/video will be taken using multiple camera unit, but mostly using cameras that are facing terrains below. and send back to airborne server or other servers. Focus of attention is determined and rough model will be created. If processing power is sufficient, this can be done in each unit. Infra-red sensors or other sensors can be used in addition to CMOS imager to identify specific signature on terrain.

* Phase-IV: Each unit deploys small and simple flaps to control trajectory, so that visual servo will be made effective to regroup IF units, so that areas that are more significant will be assigned with dense IF units. Photo/video analysis and reconstruction continues. In low altitude, all 360 angle camera as well as microphone and other sensors are activated to capture maximum information on the ground. If possible, frame rate will be increase dramatically.

∗ Phase-V: For those units that safely reached the ground and survived impact, 360 degree vision and microphone systems, as well as other sensors will be activated to identify objects and terrain structure.

This approach integrates self-organization of agents and sensory feedback on-the-fly, and can be enormously useful for rapid deployment at disaster site, as well as being an excellent test of modern AI techniques.

Conclusion

This paper addressed several issues in robust systems for RoboCup domains. Several aspects of robustness have been identified, and four aspects of information fusion have been discussed briefly. Both soccer and rescue provides an excellent platform for such research, and several research issues have been raised. Integration of three dimensions (abstraction levels, perception modality, and perception-action loops) of information fusion poses particularly interesting problems that community shall tackle. Spatio-temporal integration applies to both soccer and rescue, but more seriously to rescue scenario. Resolving this issue requires not only improvement of each robotic and AI agents, but also how such systems are deployed before and after the onset of the disaster. A systematic approach for various levels of information fusion is necessary for robust perception of multi-agent teams.

References

1. Kitano, H., *Systems biology: a brief overview.* Science, 2002. **295**(5560): p. 1662-4.
2. Kitano, H., *Computational systems biology.* Nature, 2002. **420**(6912): p. 206-10.
3. Nakadai, K., Lourens, T., Okuno, H.G., and Kitano, H. *Active Audition for Humanoid*. in *Proceedings of the Seventeenth National Conference on Artificial Intelligence*. 2000. Austin, Texas: The AAAI Press.
4. Nakadai, K., Hidai, K., Mizoguchi, H., Okuno, H.G., and Kitano, H. *Real-Time Auditory and Visual Multiple-Object Tracking for Robots*. in *Proceedings of the Seventeenth International Joint Conference on Artificial Intelligence*. 2001. Seattle: The AAAI Press.
5. Nakadai, K., Hidai, K., Okuno, H.G., and Kitano, H. *Real-Time Speaker Localization and Speech Separation by Audio-Visual Integration*. in *Proceedings of IEEE/RSJ International Conference on Robots and Automation*. 2002. Washington DC: IEEE.
6. Ballard, D. *Reference Frames for Animate Vision*. in *Proc. of International Joint Conference on Artificial Intelligence*. 1989. Detroit.
7. Alon, U., et al., *Robustness in bacterial chemotaxis.* Nature, 1999. **397**(6715): p. 168-71.
8. Yi, T.M., et al., *Robust perfect adaptation in bacterial chemotaxis through integral feedback control.* Proc Natl Acad Sci U S A, 2000. **97**(9): p. 4649-53.
9. Nakagawa, Y., Okuno, H.G., and Kitano, H. *Using Vision to Improve Sound Source Separation*. in *Proceedings of the Sixteenth National Conference on Artificial Intelligenc*. 1999. Orland: The AAAI Press.
10. Kitano, H., *Challenges in robust situation recognition through information fusion for mission critical multi-agent systems*, in *RoboCup-2003*. 2004, Springer.

Chapter 2: Biological Robustness: A Basis for Robust Architecture

The architecture described in chapter 1 is a result of investigation on biological robustness. Basic principles identified in biological system have been reformulated into engineering system framework.

This chapter describes biological frameworks that supports rational behind the proposed architecture.

2.1 Biological Robustness

Discovery of fundamental, system-level principles behind complex biological systems is a prime scientific goal of systems biology [1,2]. Robustness is a property of the system to maintain its functions despite various external and internal perturbations. It is one of the fundamental and ubiquitously observed phenomena exhibited at the system-level that cannot be understood by looking at the components alone. System must be robust to be able to function under unpredictable environment using sloppy components. Understanding the origin and principles of robustness in biological systems will help us put various biological phenomena into perspective; it will also catalyze the formation of principles at the system-level.

In this article, I argue that robustness is a fundamental feature of evolvable complex systems; complex biological systems shall be robust against environmental and genetic perturbations to be evolvable, and evolution often selects traits that may enhance robustness of the organism. Thus, robustness is ubiquitous in living organisms that have evolved. However, systems that are robust face fragility and performance setback as an inherent trade-off. Identification of a basic architecture for a robust system and trade-offs embraced is essential for understanding their faults and countermeasures – diseases and therapies.

Robustness as an organizational principle

Robustness enables the system to maintain its functionalities against external and internal perturbations. Such a property has been widely observed across species, from gene transcription level to systemic homeostasis level. For example, fate decision of lambda phage, which either lysis or lysogeny pathways has to be activated, was once considered a result of fine tuning of binding affinity of promoters and corresponding regulatory factors. However, it was shown that it was the structure of the network that involves both positive and negative feedback that is responsible for making sustainable commitment, and not the specific binding affinity, therefore the fate decision behavior was shown to be robust against point mutations in the promoter region [3]. In addition, cooperative binding of repressors that forms implicit local positive feedback also contribute to stability of the switch [4-6]. *Escherichia coli* is capable of maintaining chemotaxis behavior over an extremely wide range of chemo-attractant concentration due to intracellular integral feedback that ensures perfect adaptation that is independent of ligand concentration [7-9]. A biochemical network involved in segmental polarity in *Drosophila* has been shown to be robust against changes in initial values and rate constants of interactions involved that enables stable pattern formation [10,11]. Similar observations have also been made on morphogen patterns formations[10,12,13]. Diseases such as cancer and diabetes are manifestation of co-opted robustness in which mechanisms to protect our body are effectively taken-over to sustain and promote the epidemic states [14-16]. There are many more examples of robust properties observed in various biological systems. As studies accumulate, it is now important to provide an integrated perspective on robustness of biological systems.

Robustness of a system may manifest itself in two ways: the system returns to current attractor or transit to a new attractor that ultimately maintains system's functions (Figure 1). An attractor is a point or an orbit in the state space where state of the system asymptotically converge. A return to the current attractor is often called "robust adaptation". The attractor can be either static (a point attractor; a fixed point in the phase space in which trajectory of the system state asymptotically approaches) or oscillatory (a periodic attractor; a cyclic orbit in the phase space in which the trajectory system state asymptotically approaches). A transition into a new attractor has to be made robustly in response to stimuli, so that the system behaves consistently against perturbations. As seen in lambda phage fate decision, stochastic process often influences trajectory of transition and eventual attractor the system converge. It is often misunderstood that robustness is to stay unchanged regardless of stimuli and mutations, so that the structure and components of the system, hence state of operation, is unaffected. However, robustness actually means maintenance of specific functionalities of the system against perturbations and it often requires the system to change its state of operations in a flexible way. In the other word, robustness allows changes in the structure and components of the system due to perturbations, but specific functions are maintained.

In the following sections, I will outline the mechanisms assuring the robust operation of a system, i.e., system control, alternative, modularity and decoupling.

System control. System control is a mechanism that consists negative and positive feedback to attain robust dynamic response observed in a broad range of regulatory networks, such as cell cycle, circadian clock, chemotaxis, etc [7,17,18]. Negative feedback is the prime mode of control that enables robust response (or robust adaptation) to various perturbations. Bacteria chemotaxis is one of the best studied example of robust adaptation that uses negative feedback, an integral feedback in particular, to attain perfect adaptation that enables chemotaxis against broad range of stimuli [7-9]. It was shown that particular control strategy, an integral feedback, is essential to maintain robust adaptation in both *E. coli* and *Bacillus subtilis* despite the fact that network topologies are not identical [19].

Positive feedback contributes to robustness by amplifying the stimuli, often producing bi-stability, so that the activation level of the following pathway can be clearly distinguished from non-stimulated states and such state can be maintained. In *Drosophila* segment polarity formation, repetitive stripes of differential genes expressions are observed. The first stripe has to express *wingless (wg)*, the second stripe has to express *engrained (en)*, and the third stripe expresses neither. A computational model is created by von Dassow and colleagues initially without positive autoregulatory feedback on *wg* and *en*, but failed to reproduce experimentally observed patterns. However, with two positive feedbacks inserted on *wg* and *en* activations, robust pattern formation was reproduced [10]. Recently, Ingolia analyzed this model and showed that the bi-stability caused by positive feedback loops are responsible for robust pattern formation [11].

Positive feedback is also used in signal transduction and cell cycle to form switch-like behaviors of the system by amplification of stimuli as well as for fate decision as seen in the lambda phage, so that it initiatives transition and a new state of the system is made more robust against noise and fluctuations of stimuli[3,20-27]. Many biological subsystems use combination of such system control to attain their functions and its robustness[27,28].

Alternative, or fail-safe (Redundancy and Diversity). Robustness can be enhanced if there are multiple means to achieve a specific function, because failure of one of the means can be backed up by other means available. I will call this mechanism as "alternative", or "fail-safe", in this paper (but a better term may need to be invented to comfortably represent the concept). This concept includes redundancy, overlapping function, and diversity with the difference in degree of similarity of available alternative means. Redundancy generally refers to situation where multiple identical, or similar, components (or modules) can back-up each other when one of the components failed. Diversity, or heterogeneity, represents the other extreme where a specific function can be ultimately attained by different means available in the population of heterogeneous components. Some of such phenomena have been well recognized as phenotypic plasticity [29-31].

In some tissues, cells may be surrounded by neighbors that are similar to them, so that damaged cells are quickly replaced by other cells. But having multiple identical components as alternatives is rare. Alternative is mostly attained by having multiple heterogeneous components and modules with overlapping functions. Recent findings strongly demonstrated that gene duplication, particularly whole genome duplication followed by extensive gene loss and specialization, is one of critical mechanisms of evolutionary innovation[32,33], providing supports for long standing hypothesis by Susumu Ohno[34]. While duplicated genes are diversified by mutation, if the function of duplicated gene pairs partly overlaps it act as an evolutional capacitor[35,36], and computational study indicates, under a certain condition, such pairs could be evolutionary stable[37]. For example, budding yeast CLB5 and CLB6 are relatively homologous genes encoding B-type cyclins, in which CLB6 shares 49.7% identical residues with CLB5, both encoded proteins are involved in S-phase entry of cell cycle[38]. Deletion of CLB6 has no or little effect and deletion of CLB5 has prolonged S-phase, but deletion of both genes impedes proper timely initiation of DNA replication. This is an example of genes that share some functions, but not totally identical.

There are numerous examples of alternatives at network-level, too. Text-book examples include glycolysis and oxidative phosphorylation [39]. Although both processes produce ATP, the oxidative phosphorylation requires constant supply of oxygen, whereas glycolysis can be either aerobic or anaerobic, although the latter is much less efficient. DIAUXIC SHIFT in yeast causes drastic change in metabolic pathways, depending on whether glucose or ethanol is available for energy metabolism [40]. The flux balance of metabolic pathways is readjusted depending on the available resources in the environment, but either pathway ultimately serve to produce essential materials for survival and growth [41,42]. These are examples of phenotypic plasticity often consider to the opposite of robustness. However, I argue it is more consistent to view phenotypic plasticity as a part of robustness, because such plasticity enables organisms to robustly adapt to varying environment.

It is interesting to note here that while redundancy by duplicated genes is frequently observed, where is no reported case of duplicated circuits despite the fact that there are numbers of circuits with similar topologies. Investigation of networks that share similar topology as far as the degree of homologous genes involved in each network is concerned revealed that while genes may be duplicated, network as a whole is not duplicated [43]. This indicates that similar network topologies in different places within and between species are due to convergent evolution, rather than duplications [43,44]. This is consistent with the fact that circuit level alternative are attained by different implementations of overlapping functions.

It is important to understand that alternative is coupled with system control, rather than being totally independent. First, having alternatives at components level enables regulatory feedback to remain intact against mutations. Second, switch between alternative means has to be orchestrated by specific control, so that system behaviors are properly maintained.

Modularity. Modularity is an effective mechanism to locally contain perturbations and damages, so that the effects on the whole system can be minimized. Module is widely observed in various aspects of organisms serving as a possible biological design principles [30,45,46], and an essential element in engineering and industry [47,48]. Despite intuitive consensus, the concept is still ambiguous and it is sometime hard to detect[46]. A cell is an obvious example of such a module that constitutes multi-cellular systems, and it interacts with environment and other cells mainly through receptors, ion channels, etc. Modules are often hierarchically organized; a cell itself is composed of organelles, such as mitochondria, at the same time, it is also a part of larger modules such as tissues and organs. Aside from physical modules such as a cell, there are functional, spatial and temporal modules that can be recognized as subsystems of metabolic network, signal transduction, and developmental regulatory networks. Bacteria flagella and its control module represents both physical and logical module that is robust and versatile [49]. Although such modules do exist, as seen in segmental polarity networks [10,11] and elsewhere [50], they are often less obvious than physically partitioned modules and engineering modules.

Decoupling. Decoupling isolates low-level variation from high-level functionalities. For example, Hsp90 not only fixing proteins that are mis-folded due to environmental stresses, but also decouples genetic variations from phenotype using the very same mechanism, thus providing the genetic buffer against mutations [51-53]. Such genetic buffers decouple the genotype from the phenotype and provide robustness to cope with mutation, whilst maintaining a degree of genetic diversity. These buffers have been shown to underpin the robustness of developmental processes such as Waddington's canalization[54]. Importantly, the mutations that are masked by genetic buffering are neutral to the selection (one of the premise of Kimura's NEUTRAL THEORY OF EVOLUTION[55,56]), thus providing a source of material for the evolution of the system during extreme perturbations.
Feedback controls sometimes compensate for changes in kinetic constants and initial values of networks, as seen in bacteria chemotaxis[7-9] and *Drosophila* segmentation[10], or even mitigate the impact of loss-of-function mutant, so that apparent phenotype may not be shown. A computational study on cell cycle, originally aimed for evaluating model validity, demonstrates that removing some genes does not always eliminate cell cycle, but it is only made more fragile against perturbations [17]. Bistability created by positivie feedback sometimes decouples fluctuations at molecular level, such as numbers of molecules involved in reactions, from the committed state of the system. Thus, dynamics of networks often provides decoupling against both genetic and environmental perturbations[57]. There are even a hypothesis, albeit computational, claiming such buffering is an intrinsic nature of complex networks [58-60].

Another possible decoupling may be taking place between information encoding and conversion of dosage of stimulus into pulse of protein activations. Upon DNA damage, p53-MDM2 feedback loops generate oscillatory behaviors, and such a behavior was recently found to be a potential converter of graded stimuli (degree of DNA damage) to digital pulse (peak of p53 activation), so that only numbers of pulses matters after the conversion [61,62].

The mechanisms behind robustness can be intuitively understood using an example of a sophisticated engineering object, such as an airplane (Figure 2). It is instructive to know that very similar mechanisms also exists in a variety of sophisticated engineering systems that must be build on less than perfect components and has to cope with unpredictable environment, suggesting universal nature of robustness. Interesting questions here are whether there is fundamental system architecture for successful robust systems, and what are limitations and risks of associate with such systems.

The Origin of Robustness

It is now increasingly recognized that robustness is ubiquitous. So what are the principles and mechanisms that lead to the emergence of robustness in biological systems? My conjecture is that robustness is an inherent property of evolving complex dynamical systems, meaning various mechanisms incurring robustness of organisms actually facilitate evolution, and evolution selects robust traits. Therefore, requirements for robustness and evolvability are almost identical. This implies that there are architectural requirements for complex systems to be evolvable, which essentially requires the system to be robust against environmental and genetic perturbations. Robustness is ubiquitous because living organisms have evolved.

Evolvability requires flexibility in generating diverse phenotype by means of producing non-lethal mutations [45,63,64]. Kirschner and Gerhart define evolvability, or evolutionary adaptability, as a capacity to generate heritable and selectable phenotypic variations that consists of features that “reduce the potential lethality of mutations and the number of mutations needed to produce phenotypically novel traits”[63]. They argue that flexible versatile proteins, weak linkage, exploratory systems, and compartmentalization are central features that fosters evolvability [63]. They also argue that the emerging global architecture shall be composed of highly conserved core-processes that are co-selected with various processes some of which brings phenotypically novel traits.

Such features can be translated into architectural requirements of the system that is consistent with that of robust systems. First, there must be mechanisms to maintain components and interactions intact against mutations, yet capable of generating genetic variations. Second, there must be modules that robustly maintain their functions against external perturbations and mutations. Third, there must be highly conserved core-processes, which are also modular, that bear fundamental functions, such as metabolism, cell cycle, and transcriptional machinery, where variety of modules can be interfaced to create diverse phenotypes. The overall architecture that meets such requirements is most likely to be a modularized nested bow-tie, or hour-glass, structure where various inputs and outputs modules are connected to conserved core (Figure 3), a structure also identified as a structure of the Web[65]. Such bow-tie structure appears is various aspects of biological systems from global structure to specific mechanisms such as transcription and translation processes [66]. The architectural features entailed in this modularized bow-tie structure better offers robustness to the various aspects of system.

Buffering

The first step in robustness is to maintain components and interactions intact against perturbations. As already discussed, chaperons including hsp90 fix proteins misfolded due to external stresses such as heat shock. This mechanism also applies to fixing of proteins that are genetically varied, but expose masked genetic variations when such mechanisms are impeded[53]. Networks also contribute to such buffering[57]. This is particularly the case when it is robust against external perturbations, because regulatory feedbacks also provides robustness to perturbation of various internal parameters, as already discussed in chemotaxis[7] and developmental modules[10]. Genetic buffering, also called evolutionary capacitor, either attained by chaperons or network, is one of the fundamental mechanisms to provide both robustness and evolvability. There is increasing recognition that robustness against mutations may be evolved by congruence that is side effects of robustness against environmental perturbations and emergent property of complex networks[67].

Robust Modules

In principle, a modular system enables generation of diverse phenotype by rearrangements of its inter-module connections and relatively independent evolution of each module through mutations. If the system is tightly integrated without modular structure, any change in any part of the system may have major impact on other parts of the system, and slight changes in stimuli or noise may results in a major unexpected and undesirable outcome. The system will be intractable, and it is very difficult for such systems to generate new phenotypes without lethal effects – the system is too complicated to touch. Modularization significantly mitigates this problem by enabling each module to function relatively autonomously from others. However simply having modules is not enough to be evolvable. It must be robust against various perturbations such as changes in stimuli, internal kinetic constants, and mutations. This feature is essential because modules need to be able to cope with changes in stimuli from adjacent modules that might evolve somewhat independently or function in the different context. Such robustness is attained by system control and alternatives embraced within each module.

The contribution of system control to the module robustness is particularly important in developmental processes where novel morphologies can be explored during evolution. The segment polarity network in *Drosophila* was shown to be robust against variations in kinetic parameters and initial concentrations of relevant proteins, as long as central network structure is maintained[10]. Similar type of robustness was also identified in BMP MORPHOGEN gradient formation[68]. ORGANIZING CENTRE is a good example of robust buffering of variation in development[69,70]. A portion of developmental processes is tolerant against variations in initial values and robustly forms patterns that serve as a basis for further elaborations in developmental patterning, amenable to reuse under different context[71,72]. Hox genes signifies the power of modularity where changes in Hox cluster alone affects basic body plan as a network of genes downstream of the gene develop a part of body segment relatively autonomously from other part of the body[73-75]. Mutations in Antenapedia (*antp*) and eyeless (*ey*) exemplifies master control genes can ectopically develop appendages and being non-lethal in laboratory environment[76-78], although viability of such phenotype in natural environment is questionable. It is important to recognize that non-lethal phenotype does not means such phenotype is favored in selection.

Signal transduction pathways play important role in phenotypical diversity during evolution. Hedgehog (Hh), wingless related (Wnt), TGF-beta, receptor tyrosine kinase (RTK), Notch, JAK/STAT, and nuclear hormone pathways are signal transduction pathways widely used in various aspects of developmental process. Co-option of signal transduction pathways by which existing pathways are used for different processes is considered one of the critical features in evolution, as observed in Hh signaling pathway that is used in wing pattern formation is co-opted in butterfly eyespots pattern formation[71]. Numbers of signal transduction cascades combined both negative and positive feedback loops, and have shown to be robust against variations of stimuli and kinetic constants so that it can maintain normal cellular physiology as well as developmental processes [25,26,28,79,80]. This intrinsic robustness of the pathway enables co-option, so that novel morphologies can be generated.

The origin of modularity is still controversial. It is certainly an evolved property, not necessarily selectable trait by itself, and it enhances flexible generation of various phenotypes in development[81]. At the same time, modular structures and modular regulatory networks within a single cell and bacteria that demonstrate enormous diversity and evolution of such modules indicate flexibility of development is not the only reason for modularity. Here, I would discuss two possible reasons that modularity initially emerged because it provides robustness against environmental perturbations.

First, emergence of modularity of gene regulations may needed handle diverse and complex stimuli and responses[49]. It is essential that signaling networks and reaction related networks are modularized to some extend in order to cope with various external perturbations without mixing up stimuli and responses relationship, as well as to prevent effects of environmental perturbations to spread system-wide.

Second, if modularized phenotype, in both morphology and regulatory networks, has selective advantage due to robustness against environmental perturbations, modular developmental processes may be co-selected because it better generates modular phenotype. This hypothesis assumes that modular phenotype has selective advantage and modular developmental processes better generates modular phenotype; neither of them yet to be tested. If these two reasons hold, modularity may be originated to bear robustness against environmental perturbations, but congruent with flexibility of development.

The Architectural Framework

There are two architectural features that facilitate evolvability and robustness [63,64]: highly conserved core processes that are interfaced with diverse inputs (signaling and nutrients) and outputs (reactions and products) and versatile mechanisms that bear essential processes of the system, so that any new processes that properly interface with this mechanism can utilize such common mechanisms, called “weak linkage”[63]. These features represent the bow-tie architecture in different scale; a global topology or specific processes. The bow-tie structure is modular and nested, so that it appears in various aspects of biological systems. Here, I argue that bow-tie is real, robust, and facilitate evolvability.

Bow-tie is real

Genome-wide analysis revealed intriguing characteristics of biological networks that support bow-tie structure. It has been proposed that global structure of metabolic networks and protein interaction networks are scale free network created by preferential attachment[82,83]. Scale free networks are tolerant against random removal of node, but fragile against systematic removal of nodes with high connectivity[84]. Ma and Zeng considered directionality of reactions in the analysis of metabolic networks of 65 fully sequenced organisms, and found that the overall structure of the network exhibits a 'bow-tie' structure, instead of scale free network, in which a big highly connected core cluster is interfaced with less connected IN and OUT clusters[85]. The core of the network is a giant strong component (GSC) sub-network which has very tight connections among its components[85]. They have further investigated essential ingredients of GSC across species. Comparison of the metabolic networks between *Streptococcus pneumoniae* and *Pyrococcus furiosus* demonstrates conservation of essential metabolic pathways, such as the TCA cycle, pentosephosphate pathway, and glycolysis pathway, within GSC; this conserved core pathways is shown to be robust against perturbations [85].

Another indication of the existence of such conserved processes and exploratory processes comes from comparative studies using functional annotation of 150 fully sequenced genomes[86,87]. The Gene Ontology's biological process hierarchy[88] was used to annotate functional categories to each gene, and proportions of numbers of genes in each functional category for all 150 species were counted. A scaling exponent is defined where it is 1.0 when number of genes in a category doubled when total number of genes doubled, less than 1.0 when number of genes in a category is less than rate of increase of total gene number. Cross species study on 65 bacteria genome indicates basic biological processes has scaling exponent less than 1.0 that includes cell cycle (0.47 ± 0.08), DNA repair (0.64 ± 0.08), DNA replication (0.43 ± 0.08), and protein biosynthesis (0.13 ± 0.02), but processes that may generate evolutionary novelty tend to have scaling exponent over 1.0 such as transcriptional regulation (1.87 ± 0.13), signal transduction (1.72 ± 0.18), ion transport (1.42 ± 0.28), two-component systems (2.07 ± 0.21), and cell communication (1.81 ± 0.19)[86]. This tendency is consistent in extended study using 15 Archaea, 116 Bacteria, and 10 Eukaryota genomes[87]. In addition, scaling exponent for genes in defense response category in Eukaryotes genomes was 3.35 ± 1.41, highest in all categories[86]. This illustrates that there are highly conserved processes bearing fundamental biological processes, such as biosynthesis and DNA replications, that form core processes and weak linkage, as well as processes added with increased genome size possibly bearing generation of variety of cell-types and morphological features, such as signal transduction, transcriptional regulation, and intercellular communications. This implies new pathways may be constantly added to wings of bow-tie with increase of genome size.

"Weak linkage" [64] enables addition of new processes to the existing core process using common mechanisms. It is a common versatile mechanism that operates on diverse inputs and outputs, such as ion channel, G-protein, and transcription machinery. If transcription machinery is different for each gene, addition of new genes and new transcriptional regulations require invention of customized transcription machinery that makes evolution nearly impossible. GTP-binding proteins and the downstream cAMP and calcium dynamics, as well as ion channels also represent systems with common underlying mechanisms that allow new repertoire to be added [64,89]. Various receptor channels, receptor tyrosine kinase (RTK), and GPCR, through diverse mechanisms and adenylyl cyclase isoforms converge mainly to second messengers, such as cAMP and calcium ions, that mediates variety of cellular responses, such as cell movement, cell growth, metabolism, etc [89]. Cdc42, a Rho family of GTPases, is another example of common regulators where various RTK and GPCR pathways converges, and mediates various cellular responses[90]. Most signal transduction cascades mainly converge to modulate limited numbers of second messengers, but signaling pathways are often diverse and cross-talked[91,92]. There is a specific pattern of interaction that characterizes logic behind it, such as receptor and subunit structures of G-protein, G-Protein activation by ligand-bounded receptors, signaling to downstream, etc. This is a protocol[93], so that diverse signaling pathway can be created by numerous isoforms as far as this protocol is kept, and contribute to diverse, but consistent, signaling leading to weak linkage and covered core. These are manifestation of bow-tie structure for specific processes, such as signal transduction.

Bow-Tie is robust

Whether bow-tie structure provides robustness against external perturbations depends upon robustness of the conserved core and global regulations imposed. Ma and Zeng argues that GSC, a conserved core of the metabolic network, is robust against mutations because there are multiple routes between any pair of nodes within GSC[85].
Variety of stimuli activates signal transduction pathways converged to modulate second messengers, such as cAMP, cGMP, and calcium ions, and in turn activates variety of cellular responses. Here, second messengers are the conserved core of the bow-tie

architecture, and has to be maintained robustly. cAMP, for example, is produced from adenylyl cyclases by ATP. Interestingly, there is a variety of adenylyl cyclase isoforms involved in multiple pathways possibly creating alternative pathways. ATP is supplied from a robust metabolic core mechanism that is also a bow-tie structure. Here, the bow-tie structure at metabolism level supports the bow-tie structure at signal transduction.

In addition to the robustness of the conserved core, the bow tie architecture may provide advantage in generating coordinated response to variety of stimuli, hence improves robustness against external perturbation, by having variety of inputs connecting to the robust core where variety of reactions are mediated. Direct association between stimuli and reactions, without using the robust core, requires extensive individual controls to attain coordinated response, and disruption in any of such regulation may seriously undermine system behaviors. Unless each stimuli reaction can be regarded as independent, so that coordination is not required, control through the common robust core may better provides robustness of the system.

One might ask if such mechanisms enable to accommodate vast diversity of possible phenotype. In fact, versatile mechanisms are essential to accommodate variety of possible input stimuli and reactions in a consistent manner, because addition of new signal transductions, for example, only needs to be interfaced with existing machinery without inventing an entire cascade. For example, recent findings of differential tissue and cell-type specific expression of GPCRs in human and mouse[94] provide explanations on how variety of cells may utilize the conserved core and weak linage mechanisms. Expression pattern analyses using RT-PCT on 100 randomly selected endoGPCR, GPCR for ligands of endogenous origins, from 392 mouse endoGPCR over 26 tissues, 17 from peripheral tissues and 9 from different brain regions, revealed that each endoGPCR is expressed in numbers of different tissues, but forming unique combination of endoGPCR for each tissue[94]. This suggest a possibility a relatively small set of second messengers are used in different context enabling differentiation into variety of cell tpes and a range of cellular responses. Same argument also applies to toolkit[72], that is limited set of versatile genetic networks, because they can be used in different context.

Conservation of Robustness

Since robustness is ubiquitous and inherent feature of biological systems, it is important to understand intrinsic dynamics of such systems. It is interesting to ask whether there is principle of conservation and symmetry as seen in physics. I suggest that there may be similar principles for robustness of the biological systems, although they could require representation that is not as simple as their counterparts in physics. Here, I will discuss theoretical properties of such systems.

I have argued that robustness is a fundamental feature that enables complex systems to evolve, and evolution enhances robustness of organisms. One possible path following this scenario is increasing complexity of organisms by successive addition of regulatory systems, such as diverse regulations, signal transduction pathways, RNA regulations[95-97], and histone modifications[98], to enhance robustness against specific environmental perturbations and exploration into un-occupied niche[99]. However, introduction of various control loops generates trade-off by causing instability when unexpected perturbations are encountered, leading to catastrophic failure. It is widely accepted in the control theory, that increased robustness against non-linearity and noise using negative feedback control is associated with instability elsewhere. Carlson and Doyle tried to generalize such issues in their highly optimized tolerance (HOT) theory by arguing that systems that are evolved to be robust against general perturbations are extremely fragile against certain types of rare perturbations[100,101]. Using simplified models in physics, forest fire, etc, they argued that systems that are successively optimized to certain type of perturbations develop a characteristic structure which is efficient and robust to cope with such perturbations, but could be extremely fragile against unexpected perturbations. In dynamical systems, such evolutionary optimizations are done by successively adding feedback controls to the system. It is important to recognize that while HOT describes behaviors of complex systems designed or evolved toward optimality (while it may be suboptimal) against perturbations (like modern airplanes and biological systems), other self-organization models such as scale free network[83,102] by preferential attachment and self organized criticality (SOC)[103] models systems with stochastic additions of complexity without design or evolution involved (like sand piles). Nature of robustness and fragility predicted by HOT model is generally consistent with observed properties of designed complex systems and sharply different from other model[100,101]. Csete and Doyle further argued that robustness/fragility trade-offs indicate that robustness is a conserved quantity, a concept that also applies to biological systems[93].

Take an airplane example again. The Wright brothers' airplane is not robust against atmospheric perturbations, whereas modern commercial airplanes are extremely robust against such perturbations. However, modern airplanes are extremely fragile against very unusual perturbation such as total power failure because their flight control system is totally dependent on electricity (obviously, all possible counter measures are taken to prevent such failures). Wright flyer, on the other hand, has no impact on such failure as it does not use electric control in the first place. It is important to understand such trade-offs because diseases are often manifestation of such fragility, as I will discuss later.

Fragility is not the only cost of the improved robustness. In electronic circuit design, the use of negative feedback control attains improved response against a certain range of inputs by sacrificing an overall gain of the amplifier. Thus, the use of negative feedback control gains robustness within a certain range of inputs at the cost of an aspect of performance and fragility elsewhere. Such trade-off between robustness, fragility, and performance can be widely observed in biological systems at different levels.

Having alternatives and modularity also enhances robustness, but at the cost of increased resource demands. For example, a probability of a function to fail with a single component to attain this function is P, where P is a probability of failure of the component. A probability of the function to fail with two components to back up each other will be reduced to $(1-P)^2$. However, resource requirement is doubled. Such a trade-off is effectively mitigated in biological systems because components involved tend to have overlapping functions, instead of being identical copies. Having identical copies as alternatives is only efficient when failure rate, or turn over rate, is expected to be very high. Modularity also trade-off between robustness, flexibility, and resource demands. Merging modules to share common circuits and components reduces resource needs, but robustness in preventing spread of perturbation and flexibility of rearrangement are seriously compromised.

Although several trade-off exists in robust complex systems, trade off involving system control is the most significant one. It defines dynamical properties of the biological systems which illustrate how complex biological systems behave when perturbed, as well as orchestrates how alternative components and modules are re-routed to ensure robustness of the whole system. Due to intrinsic trade-offs discussed above, it is not possible to simply increase general robustness of the system without sacrifice of performance and increased resource demands.

Co-opted robustness: system-level view of disease and therapy

Theoretically underlined properties of robust evolvable systems have direct consequences in our understanding of diseases and therapy design. First, robust systems, whether biologic or engineering, are most vulnerable when its fragility is exposed. Diabetes mellitus, for example, can be considered as an exposed fragility of the system that has acquired robustness against near-starvation, high energy utilization life style and high risk of infection, but unusually perturbed by over-nutrition and low energy utilization lifestyle[16]. Second, the system is relatively tolerant with simple "fail-off" of components, such as removal of some components or cells, due to alternatives available and as intrinsic nature of the bow-tie architecture. However, the system is vulnerable is when components "fail-on" where components are not being removed, but behave inappropriately. In engineering field, such failure is known as the Byzantine Generals Problems, named after the problem of the Byzantine army with traitors among own generals who send confusing messages, that has not yet fully solved[104]. Third, epidemic state may exhibit robustness against natural and therapeutic countermeasures if intrinsic mechanisms for robustness of our body are co-opted. The worst scenario is that fragility is exposed that triggers outbreak of disease which causes fail-on failure, and such fail-on failure persists by taking over intrinsic robustness of our body, so that an epidemic state is locked-in.

This view, which is theoretically motivated, is particularly important because intrinsic nature of diseases and appropriate countermeasures are different depends on which scenario the system failure follows. For example, cholera toxin interacts with Gs-alpha submit to trigger the symptoms[105,106]. However, it can be simply removed by antibiotics, because robustness has not been hijacked. Thus, typical counter measures involve preventing a cascade of failures by supplying waters to prevent excessive loss of liquid and using antibiotics (tetracycline) to remove pathogens by inhibiting protein production.

However, cancer and HIV represents worst scenario that epidemic state are maintained and even promoted because of intrinsic robustness mechanisms of host system. Counter measures for such diseases may be; (1) to actively perturb specific interactions or components to maintain or reduce robustness, (2) to find a point of fragility "Achilleus's heel" that is inherent in robust systems, and (3) to retake control of epidemic state by introducing counter-acting decoy "Trojan horse" or a new regulatory feedback.

Cancer represents nightmare scenario where fail-on components, tumour cells, acquired robustness against natural defense and various therapeutic interventions. Cancer is a highly robust disease in which tumour proliferates and metastasizes, in some cases despite much therapeutic efforts. Although anti-cancer drugs may temporarily reduce tumour mass, it relapses in many cases and cure is still rare. The difficulty of treating tumours is due to acquired robustness, partly as a result of co-opting intrinsic mechanisms for robustness [14,15]. High level of genetic heterogeneity in the tumour that forms heterogeneous redundancy and multiple feedback loops in both cellular and tumour-host environment account for robustness of cancer. Genetic heterogeneity within a tumour cluster due to chromosome instability generates high level of heterogeneous redundancy in a function to survive and proliferate. This heterogeneous redundancy allows some malignant cells to tolerate a therapy and reform a tumour. Mechanisms that maintain normal functions of the body also function to enhance tumour's robustness against therapy. For example, drug resistance is caused by up-regulation of *MDR1* and other genes that pump out toxic chemicals from the cell; so a function that protects us in normal condition, is exploited in tumour to protect malignant cells. A low oxygen supply (hypoxia) caused during the tumour cluster development is countered by metabolic shift from oxygen-dependent TCA cycle to glycolysis, as well as activating feedback loop by up-regulating *HIF1*, which up-regulates VEGF to promote angiogenesis, and MMP, uPAR, and CRCX4 that promote tumour cell metastasis [107], a series of responses that protects us in general low oxygen conditions.

From the robustness perspective, possible clinical strategies against cancer are; to control robustness of tumour, and to finding out the point of fragility that is inherent in the robust system. To control robustness, therapy should be directed to induce tumour dormancy by selectively inducing cell cycle arrest, rather than aiming at tumour eradication, because one source of robustness is genetic heterogeneity created through somatic recombination. Apart of specific cases where tumour cells are relatively homogeneous so that drugs that targets specific molecule can have dramatic effects, tumour mass reduction may not be an appropriate therapeutic goal, because of a high risk of relapse if the reduced tumour gained greater level of heterogeneity that includes mutant cells highly resistant against therapeutic efforts. Controlling tumour robustness would be a genuine measure of therapeutic efficacy, so that the risk of relapse can be well controlled. The other approach may be to find fragility of tumour. Since tumours undergo clonal evolution and acquire robustness against a range of therapies, the principle of conservation of robustness indicates there must be the point of extreme fragility. Therefore, efforts to find fundamental fragility of tumour for therapeutic

targets should be made in future.
The question is how to find fragility that is therapeutically effective and practical. It is important here to investigate what system has been optimized for and identify sources of robustness epidemic acquired. Since fragility is a by-product of robustness elsewhere, fragile point of the system must be associated with mechanism that gave rise to enhanced robustness. For example, robustness of tumour is sustained by chromosome instability, intracellular feedback loops, and host-tumour interactions. Countermeasures to control cell cycle by multiple molecular targets possibly using RNAi, selectively de-stabilize instable chromosome, infiltrate genetically engineered tumour associated macrophage[108] to retake control of host-tumour interactions, and introduce artificial genetic circuits[109] to conditionally express tumour suppressor genes can be potential candidates, but has to be designed carefully to specifically explore frgility or to control robustness.

HIV infection is the other worst case scenario. HIV predominantly infects CD4+ T cell and replicate when CD4+ T cell activate its anti-virus responses [110-113]. Infected cells are not removed because infection is hardly detectable. This is typical case of fail-on problem. In addition, HIV creates highly diverse genetic alternation. This HIV's strategy is a hijack of robust immune response mechanism, which makes AIDS difficult to cure. Robust persistence of epidemic state through generation of genetic diversity and various feedback loops are similar to the strategy found in cancer. Possible therapeutic approaches discussed already may apply for effective treatment. Interestingly enough, one strategies proposed to combat HIV involves putting HIV into latent state, instead of trying to remove it, by introducing the decoy that is conditionally replicating HIV-1 vector (crHIV-1) [114-116]. crHIV-1 contains only *cis*, but not *trans* elements that are necessary for virus packaging, and carries antiviral genes that inhibits wild type HIV-1 functions[116]. If this is successful, it may retake control of the system, and put HIV-1 virus in prolonged latency.

Toward the theory of biological robustness

Given the importance of robustness for understanding of principle of life and medical implications, it is an intriguing challenge to formulate mathematically solid, and possibly unified theory of biological robustness that may serve as a basic organizational principle of biological systems; some early attempts date back to the middle of the last century [117,118]. Such a unified theory could be a bridge between fundamental principles of life, medical practice, engineering, physics and chemistry. This is a major challenge in which numbers of issues that has to be solved particularly to establish mathematically well-founded theories, but the impact would be enormous.

First, solid quantitative index of the robustness has yet to be established. Such index has to be able to equate with experimentally measurable quantities, so that hypotheses on the degree of robustness can be tested experimentally. There are several concepts on STABILITY OF THE SYSTEM in CONTROL THEORY[119], and some attempt has been made to apply such ideas to biological robustness[120]. In non-linear dynamics theory, there is a concept of lyapunov stability that represents system's tendency to asymptotically return to the attractor. However, practical application of these concepts to biological systems has been limited, mainly due to an enormous degree of dimensionality and non-linearity that are intrinsic to biological systems. Measuring perturbations for all such dimensions is impractical. Practical, yet theoretically solid, index needs to be developed to provide guidelines for selecting smaller numbers of parameters to be perturbed so that the system's response can be measured. Haken pointed out that only a few parameters are important to describe system behavior near bifurcation point[121], but this approach is too limited to analyze various behaviors of biological systems. Efforts are undergoing to develop a mathematical method to derive a set of inequities of parameters that ensure stability of the system[122,123]. While it is in infancy and has only limited applicability now, further progress in this area would certainly benefits mathematical analysis of robustness of biological systems. In experimental front, comprehensive mutant creation and dosage controlled perturbations are already practical for some organisms. Since, there are often practical aims to investigate robustness of the system such as to induce cell cycle arrest, experiments can be carefully designed to perturb relevant genes and parameters, and published data can be systematically collected, to obtain practically sufficient index of robustness for specific aspects of the organism[124].

Second, the theory that embraces various aspects of robustness has not yet been formulated. Control theory is often used to explain robustness that involves feedback regulation, but it only covers one aspect of robustness that involves negative feedback control. Furthermore, the control theory assumes that there is a certain set point that the system's state shall approach, even under perturbations, and that is assumed to be determined by the designer. Of course, there is no such designer in biological systems, and set point is implicit in the equilibrium state of the system, and such equilibrium

often changes dynamically. Theory need to be formulated to reflect such features of biological systems.
Recent efforts to integrate control theory and Shannon's channel coding theorem may provide interesting framework for feedbacks[125,126]. This theory tries to formalize cases where there is limitation of information capacity in feedback loop, so that feedback signal is potentially impeded on fidelity, noise, and delay. This better reflects reality of biological systems in which signals are transmitted with noise, delay, and compromised fidelity.

Third, challenges to relate dynamics of life and thermodynamics have yielded only a limited success. Behaviors of the physical and chemical systems near equilibrium have been well investigated in the past. LE CHATELIER-BRAUN'S PRINCIPLE provides a basis for response against perturbations for systems in equilibrium, as a special form of more general principle known as THEOREM OF MODERATION[127]. The principle indicates emergence of compensatory feedback to cope with perturbations. Efforts have been made to extend thermodynamics for far from equilibrium to explain biological phenomena[128-130], but applied only for relatively simple chemical reactions under isotropic medium such as BELOUSOV-ZHABOTINSKI (BZ) REACTIONS. Signal transduction, for example, undergoes dramatic changes in the state of the cell depending upon the intensity and types of stimuli, resembling transition from near equilibrium state to far from equilibrium state. But, this is not due to simple chemical reactions under unstructured free medium as seen in BZ reactions. Cells are highly structured and have explicit interactions and physical structures controlled by gene expressions, cytoskeleton and other regulatory systems that are optimized to be robust and evolvable. This contrasts with much favored toy examples of simple chemical reactions or sand piles that are not structured. The major challenge is to formulate theories that accounts for thermodynamics in non-isotropic, heterogeneous, and structured system, because such well established mathematical frameworks for describing such systems are not available yet. Some efforts are being made to find such a theoretical framework by assuming network structure as a basis of mathematical description[131]. However, it is still to abstract to be practically applied for biological systems. Progress in this arena will help closely connect biology, chemistry, physics, and mathematics in a coherent manner.

Conclusion

Robustness is a fundamental property of biological systems. It facilitates evolvability, and evolution selects robust traits. I have argued that there are specific architectural features for organisms to be robust that may be universal to any robust and evolvable complex systems. Systems control, modularity, alternative, and decoupling serve as basic mechanisms to provide robustness to the system, but need to be organized into coherent architecture to be effective at organism-level. Enhancement of robustness against perturbations can be made with combination of such mechanisms, but systems control is the prime mechanism for coping with environmental perturbations that requires proper dynamics. Thus, evolution of organisms can be viewed, at least in one aspect, as evolution of control systems. Modularity, alternative, and decoupling, in part, support robust maintenance of such control loops, but are also controlled by such control loops either explicitly or implicitly. There is an intriguing possibility that genetic buffering and modularity originated from robustness against environmental perturbations, and evolved to have wider applicability. It is important to realize that systems that are evolved to be robust against certain perturbations are extremely fragile to unexpected perturbations. This robust yet fragile trade-off is fundamental to complex dynamical systems. Importance of understanding architectural features of robust and evolvable system, and intrinsic nature of robustness and fragility embraced is that it dictates mode of system failures and effective counter measures --- diseases and therapies. Failures and viable counter-measures of such systems are often counter-intuitive, implies theoretically motivated robustness perspective may provide novel therapeutic approaches. The emerging field of systems biology has been trying to identify system-level properties, but simple use of massive data and computation would not effectively reveal insights for biological system and applications for medicine. The perspective on biological robustness would provide effective guiding principles for understanding various biological phenomena and design of therapies.

Acknowledgements

I would like to thank members of Sony Computer Science laboratories, Inc. and ERATO-SORST Kitano Symbiotic Systems Project for fruitful discussions, John Doyle and Marie Csete for critical reading of initial version of this article, and numbers of colleagues who discussed over e-mail, and anonymous referees for informative comments. This research is, in part, supported by ERATO-SORST Program (Japan Science and Technology Agency) to the Systems Biology Institute, the Center of Excellence program and the special coordination funds (Ministry of Education, Culture, Sports, Science, and Technology) to Keio University, and Air Force Office of Scientific Research (AFOSR/AOARD).

FIGURE 1: Robust reactions of the system: to stay or to transit

State of systems can be shown as a point in the state space. For the sake of explanation, this figure simplifies the state space into only two dimensions. Perturbations forcefully move such a point of system's state. State of the system may return to its original attractor by adapting to perturbations, often using negative feedback loop. Bacterial chemotaxis is a noteworthy example. There are basins of attractions in the state space where state of the system moves back to the attractor. If perturbation exceeds boundary, the system may move into an unstable region or transit to other attractors. Positive feedback have dual role in moving systems state away from the current attractor, or to push system into the extreme when there is an attractor for such a state. Cell cycle is a combination of positive and negative feedbacks that facilitate transition between two attractors (G1 and S/G2/M) forming a bi-stability. Often stochastic processes affect a transition between attractors, as seen in lambda phage fate decision, but maintenance of new state has to be robust against minor perturbations.

FIGURE 2: Explaining robustness by airplane

The concept of robustness is best described using the example of robustness of modern airplanes. Many commercial passenger airplanes have an automatic flight control system (AFCS) that maintains a flight path (direction, altitude, and velocity of flight) against perturbations in atmospheric conditions. This can be accomplished by feedback control in which deviations from the defined flight path are automatically corrected. AFCS is the critical component that enables robust maintenance of flight path by controlling airplane's flight control surfaces (rudder, elevator, flaps, aileron, etc) and a propulsion system (engines). AFCS is generally composed of three modules with same functions thereby maintaining redundancy, but each designed differently (heterogeneity) to avoid a common mode failure. Three computers are made modular, so that failure in one module does not affect functions of other part of the system. Such system is implemented using digital technologies that decouple low-level voltages from digital signal (ON/OFF of pulses), thereby rejecting noise to influence its functions. Although this is a very simplified explanation of the actual system, the basic concept applies to details of the system as well as to more complex systems. Although differences between man-made systems and biological systems exist, similarities are overwhelming. Fundamentally, robustness is the basic organizational principle of evolving dynamic systems, be it through evolution or competition and niche in the market and society.

FIGURE 3: The architectural framework of robust evolvable systems.
The bow-tie (or hour-glass) structure has diverse input and output that are connected through a conserved core and versatile weak linkage with extensive system control governing the dynamics. Core processes and versatile interfaces overlap or merge in some cases. This bow-tie structure appears at various level of the system, such as metabolism, signal transduction, transcription, and translation[66]. In signal transduction, diverse stimuli are initially received by receptors, signaling pathways, including diverse isoform of G-proteins, are activated, but converge mainly to second messengers that have limited variety and serve as weak linkage. Then, modulations in second messengers influence core processes to trigger differential gene expressions and diverse reactions. However, this process is not a simple flow as extensive local and global feedback regulations are imposed in every step. Metabolism takes diverse nutrients, preprocess them into precursors in which core metabolic pathways covert them into basic currencies such as ATP and NADH, and well as activating biosynthesis pathways to produce amino acid, nucleotide, sugar, etc. Transcription and translation also represent such structures where common machineries are used to decode a wide range of genetic information and produces diverse proteins, but versatile mechanisms themselves are conserved core. Various processes are interfaced with core processes through versatile interfaces, so that novel processes can be added and removed easily without seriously affecting other parts of the system.

1. Kitano, H. Systems biology: a brief overview. *Science* **295**, 1662-4 (2002).
2. Kitano, H. Computational systems biology. *Nature* **420**, 206-10 (2002).
3. Little, J. W., Shepley, D. P. & Wert, D. W. Robustness of a gene regulatory circuit. *Embo J* **18**, 4299-307 (1999).
4. Ptashne, M. *A Genetic Switch - Gene Control and Phage Lambda -* (Blackwell Scientific Publications & Cell Press, Oxford, 1987).
5. Zhu, X. M., Yin, L., Hood, L. & Ao, P. Calculating biological behaviors of epigenetic states in the phage lambda life cycle. *Funct Integr Genomics* **4**, 188-95 (2004).
6. Santillan, M. & Mackey, M. C. Why the lysogenic state of phage lambda is so stable: a mathematical modeling approach. *Biophys J* **86**, 75-84 (2004).
7. Alon, U., Surette, M. G., Barkai, N. & Leibler, S. Robustness in bacterial chemotaxis.

Nature **397**, 168-71 (1999).
8. Barkai, N. & Leibler, S. Robustness in simple biochemical networks. *Nature* **387**, 913-7 (1997).
9. Yi, T. M., Huang, Y., Simon, M. I. & Doyle, J. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *Proc Natl Acad Sci U S A* **97**, 4649-53 (2000).
10. von Dassow, G., Meir, E., Munro, E. M. & Odell, G. M. The segment polarity network is a robust developmental module. *Nature* **406**, 188-92 (2000).
11. Ingolia, N. T. Topology and robustness in the Drosophila segment polarity network. *PLoS Biol* **2**, E123 (2004).
12. Barkai, N. & Shilo, B. Modeling pattern formation: counting to two in the Drosophila egg. *Curr Biol* **12**, R493 (2002).
13. Houchmandzadeh, B., Wieschaus, E. & Leibler, S. Establishment of developmental precision and proportions in the early Drosophila embryo. *Nature* **415**, 798-802 (2002).
14. Kitano, H. Cancer robustness: tumour tactics. *Nature* **426**, 125 (2003).
15. Kitano, H. Cancer as a robust system: implications for anticancer therapy. *Nat Rev Cancer* **4**, 227-35 (2004).
16. Kitano, H. et al. Metabolic Syndrome and Robustness Trade-offs. *Diabetes* (in press).
17. Morohashi, M. et al. Robustness as a measure of plausibility in models of biochemical networks. *J Theor Biol* **216**, 19-30 (2002).
18. Borisuk, M. T. & Tyson, J. J. Bifurcation analysis of a model of mitotic control in frog eggs. *J Theor Biol* **195**, 69-85 (1998).
19. Rao, C. V., Kirby, J. R. & Arkin, A. P. Design and Diversity in Bacterial Chemotaxis: A Comparative Study in Escherichia coli and Bacillus subtilis. *PLoS Biol* **2**, E49 (2004).
20. McAdams, H. H. & Arkin, A. It's a noisy business! Genetic regulation at the nanomolar scale. *Trends Genet* **15**, 65-9 (1999).
21. Rao, C. V., Wolf, D. M. & Arkin, A. P. Control, exploitation and tolerance of intracellular noise. *Nature* **420**, 231-7 (2002).
22. McAdams, H. H. & Shapiro, L. Circuit simulation of genetic networks. *Science* **269**, 650-6 (1995).
23. Arkin, A., Ross, J. & McAdams, H. H. Stochastic kinetic analysis of developmental pathway bifurcation in phage lambda-infected Escherichia coli cells. *Genetics* **149**, 1633-48 (1998).
24. McAdams, H. H. & Arkin, A. Stochastic mechanisms in gene expression. *Proc Natl*

Acad Sci U S A **94**, 814-9 (1997).

25. Bagowski, C. P., Besser, J., Frey, C. R. & Ferrell, J. E., Jr. The JNK cascade as a biochemical switch in mammalian cells: ultrasensitive and all-or-none responses. *Curr Biol* **13**, 315-20 (2003).
26. Ferrell, J. E., Jr. Self-perpetuating states in signal transduction: positive feedback, double-negative feedback and bistability. *Curr Opin Cell Biol* **14**, 140-8 (2002).
27. Tyson, J. J., Chen, K. & Novak, B. Network dynamics and cell physiology. *Nat Rev Mol Cell Biol* **2**, 908-16 (2001).
28. Freeman, M. Feedback control of intercellular signalling in development. *Nature* **408**, 313-9 (2000).
29. Agrawal, A. A. Phenotypic plasticity in the interactions and evolution of species. *Science* **294**, 321-6 (2001).
30. West-Eberhard, M. J. *Developmental Plasticity and Evolution* (Oxford University Press, Oxford, 2003).
31. Schlichting, C. & Pigliucci, M. *Phenotypic Evolution: A Reaction Norm Perspective* (Sinauer Associates, Inc., Sunderland, MA, 1998).
32. Kellis, M., Birren, B. W. & Lander, E. S. Proof and evolutionary analysis of ancient genome duplication in the yeast Saccharomyces cerevisiae. *Nature* **428**, 617-24 (2004).
33. Langkjaer, R. B., Cliften, P. F., Johnston, M. & Piskur, J. Yeast genome duplication was followed by asynchronous differentiation of duplicated genes. *Nature* **421**, 848-52 (2003).
34. Ohno, S. *Evolution by gene duplication* (Springer-Verlag, Berlin, 1970).
35. Gu, X. Evolution of duplicate genes versus genetic robustness against null mutations. *Trends Genet* **19**, 354-6 (2003).
36. Gu, Z. et al. Role of duplicate genes in genetic robustness against null mutations. *Nature* **421**, 63-6 (2003).
37. Nowak, M. A., Boerlijst, M. C., Cooke, J. & Smith, J. M. Evolution of genetic redundancy. *Nature* **388**, 167-71 (1997).
38. Schwob, E. & Nasmyth, K. CLB5 and CLB6, a new pair of B cyclins involved in DNA replication in Saccharomyces cerevisiae. *Genes Dev* **7**, 1160-75 (1993).
39. Berg, J., Tymoczko, J. & Stryer, L. *Biochemistry, 5th edition* (W.H. Freeman, 2002).
40. DeRisi, J. L., Iyer, V. R. & Brown, P. O. Exploring the metabolic and genetic control of gene expression on a genomic scale. *Science* **278**, 680-6 (1997).
41. Edwards, J. S. & Palsson, B. O. Robustness analysis of the Escherichia coli metabolic network. *Biotechnol Prog* **16**, 927-39 (2000).

42. Edwards, J. S., Ibarra, R. U. & Palsson, B. O. In silico predictions of Escherichia coli metabolic capabilities are consistent with experimental data. *Nat Biotechnol* **19**, 125-30 (2001).
43. Conant, G. C. & Wagner, A. Convergent evolution of gene circuits. *Nat Genet* **34**, 264-6 (2003).
44. Teichmann, S. A. & Babu, M. M. Gene regulatory network growth by duplication. *Nat Genet* **36**, 492-6 (2004).
45. Hartwell, L. H., Hopfield, J. J., Leibler, S. & Murray, A. W. From molecular to modular cell biology. *Nature* **402**, C47-52 (1999).
46. Schlosser, G. & Wagner, G. (eds.) *Modularity in Development and Evolution* (The University of Chicago Press, Chicago, 2004).
47. Baldwin, C. & Clark, K. *Design Rules, Vol. 1: The Power of Modularity* (The MIT Press, Cambridge, MA, 2000).
48. Simon, H. *The Sciences and the Artificial - 3rd edition* (The MIT Press, Cambridge, MA, 1996).
49. McAdams, H. H., Srinivasan, B. & Arkin, A. P. The evolution of genetic regulatory systems in bacteria. *Nat Rev Genet* **5**, 169-78 (2004).
50. Spirin, V. & Mirny, L. A. Protein complexes and functional modules in molecular networks. *Proc Natl Acad Sci U S A* **100**, 12123-8 (2003).
51. Rutherford, S. L. & Lindquist, S. Hsp90 as a capacitor for morphological evolution. *Nature* **396**, 336-42 (1998).
52. Queitsch, C., Sangster, T. A. & Lindquist, S. Hsp90 as a capacitor of phenotypic variation. *Nature* **417**, 618-24 (2002).
53. Rutherford, S. L. Between genotype and phenotype: protein chaperones and evolvability. *Nat Rev Genet* **4**, 263-74 (2003).
54. Waddington, C. H. *The Strategy of the Genes: a Discussion of Some Aspects of Theoretical Biology* (Macmillan, New York, 1957).
55. Kimura, M. Preponderance of synonymous changes as evidence for the neutral theory of molecular evolution. *Nature* **267**, 275-6 (1977).
56. Kimura, M. The neutral theory of molecular evolution. *Sci Am* **241**, 98-100, 102, 108 passim (1979).
57. Hartman, J. L. t., Garvik, B. & Hartwell, L. Principles for the buffering of genetic variation. *Science* **291**, 1001-4 (2001).
58. Bergman, A. & Siegal, M. L. Evolutionary capacitance as a general feature of complex gene networks. *Nature* **424**, 549-52 (2003).
59. Kitami, T. & Nadeau, J. H. Biochemical networking contributes more to genetic

buffering in human and mouse metabolic pathways than does gene duplication. *Nat Genet* **32**, 191-4 (2002).

60. Siegal, M. L. & Bergman, A. Waddington's canalization revisited: developmental stability and evolution. *Proc Natl Acad Sci U S A* **99**, 10528-32 (2002).

61. Lev Bar-Or, R. et al. Generation of oscillations by the p53-Mdm2 feedback loop: a theoretical and experimental study. *Proc Natl Acad Sci U S A* **97**, 11250-5 (2000).

62. Lahav, G. et al. Dynamics of the p53-Mdm2 feedback loop in individual cells. *Nat Genet* **36**, 147-50 (2004).

63. Kirschner, M. & Gerhart, J. Evolvability. *Proc Natl Acad Sci U S A* **95**, 8420-7 (1998).

64. Gerhart, J. & Kirschner, M. *Cells, Embryos, and Evolution: Toward a Cellular and Developmental Understanding of Phenotypic Variation and Evolutionary Adaptability* (Blackwell Science, Malden, Massachusetts, 1997).

65. Broder, A. et al. in *The Nineth International World Wide Web Conference* 309-320 (Elservier Science, Amterdam, The Netherland, 2000).

66. Csete, M. E. & Doyle, J. Bow ties, metabolism and disease. *Trends in Biotechnology* **22**, 446-50 (2004).

67. de Visser, J. et al. Evolution and Detection of Genetics Robustness. *Evolution* **57**, 1959-1972 (2003).

68. Eldar, A. et al. Robustness of the BMP morphogen gradient in Drosophila embryonic patterning. *Nature* **419**, 304-8 (2002).

69. Nieuwkoop, P. D. Pattern formation in artificially activated ectoderm (Rana pipiens and Ambystoma punctatum). *Dev Biol* **7**, 255-79 (1963).

70. Nieuwkoop, P. D. Inductive interactions in early amphibian development and their general nature. *J Embryol Exp Morphol* **89 Suppl**, 333-47 (1985).

71. Pires-daSilva, A. & Sommer, R. J. The evolution of signalling pathways in animal development. *Nat Rev Genet* **4**, 39-49 (2003).

72. Carroll, S., Grenier, J. & Weatherbee, S. *From DNA to Diversity: Molecular genetics and the evolution of animal design* (Blackwell Publishing, Oxford, 2001).

73. Wagner, G. P., Amemiya, C. & Ruddle, F. Hox cluster duplications and the opportunity for evolutionary novelties. *Proc Natl Acad Sci U S A* **100**, 14603-6 (2003).

74. Gehring, W. J. *Master Control Genes in Development and Evolution: The Homeobox Story* (Yale University Press, 1998).

75. Lewis, E. B. A gene complex controlling segmentation in Drosophila. *Nature* **276**, 565-70 (1978).

76. Kaufman, T. C., Seeger, M. A. & Olsen, G. Molecular and genetic organization of the antennapedia gene complex of Drosophila melanogaster. *Adv Genet* **27**, 309-62

(1990).

77. Struhl, G. A homoeotic mutation transforming leg to antenna in Drosophila. *Nature* **292**, 635-8 (1981).

78. Halder, G., Callaerts, P. & Gehring, W. J. Induction of ectopic eyes by targeted expression of the eyeless gene in Drosophila. *Science* **267**, 1788-92 (1995).

79. Taniguchi, T. & Takaoka, A. A weak signal for strong responses: interferon-alpha/beta revisited. *Nat Rev Mol Cell Biol* **2**, 378-86 (2001).

80. Bhalla, U. S. & Iyengar, R. Robustness of the bistable behavior of a biological signaling feedback loop. *Chaos* **11**, 221-226 (2001).

81. Wagner, G. P. & Altenberg, L. Complex adaptations and the evolution of evolvability. *Evolution* **50**, 967-976 (1996).

82. Jeong, H., Tombor, B., Albert, R., Oltvai, Z. N. & Barabasi, A. L. The large-scale organization of metabolic networks. *Nature* **407**, 651-4 (2000).

83. Barabasi, A. L. & Oltvai, Z. N. Network biology: understanding the cell's functional organization. *Nat Rev Genet* **5**, 101-13 (2004).

84. Albert, R., Jeong, H. & Barabasi, A. L. Error and attack tolerance of complex networks. *Nature* **406**, 378-82 (2000).

85. Ma, H. W. & Zeng, A. P. The connectivity structure, giant strong component and centrality of metabolic networks. *Bioinformatics* **19**, 1423-30 (2003).

86. van Nimwegen, E. Scaling laws in the functional content of genomes. *Trends Genet* **19**, 479-84 (2003).

87. van Nimwegen, E. in *Power laws, Scale-free Nettworks, and Genome Biolog* (eds. Eugene & Koonin, Y. I. W., and Georgy P. Karev) (Landes Bioscience, in press).

88. Ashburner, M. et al. Gene ontology: tool for the unification of biology. The Gene Ontology Consortium. *Nat Genet* **25**, 25-9 (2000).

89. Jordan, J. D., Landau, E. M. & Iyengar, R. Signaling networks: the origins of cellular multitasking. *Cell* **103**, 193-200 (2000).

90. Jordan, J. D. & Iyengar, R. Modes of interactions between signaling pathways. *Biochem Pharmacol* **55**, 1347-52 (1998).

91. Hermans, E. Biochemical and pharmacological control of the multiplicity of coupling at G-protein-coupled receptors. *Pharmacol Ther* **99**, 25-44 (2003).

92. Werry, T. D., Wilkinson, G. F. & Willars, G. B. Mechanisms of cross-talk between G-protein-coupled receptors resulting in enhanced release of intracellular Ca2+. *Biochem J* **374**, 281-96 (2003).

93. Csete, M. E. & Doyle, J. C. Reverse engineering of biological complexity. *Science* **295**, 1664-9 (2002).

94. Vassilatis, D. K. et al. The G protein-coupled receptor repertoires of human and mouse. *Proc Natl Acad Sci U S A* **100**, 4903-8 (2003).
95. Mattick, J. S. RNA regulation: a new genetics? *Nat Rev Genet* **5**, 316-23 (2004).
96. Mattick, J. S. Non-coding RNAs: the architects of eukaryotic complexity. *EMBO Rep* **2**, 986-91 (2001).
97. Mattick, J. S. Challenging the dogma: the hidden layer of non-protein-coding RNAs in complex organisms. *Bioessays* **25**, 930-9 (2003).
98. Schreiber, S. L. & Bernstein, B. E. Signaling network model of chromatin. *Cell* **111**, 771-8 (2002).
99. Carroll, S. B. Chance and necessity: the evolution of morphological complexity and diversity. *Nature* **409**, 1102-9 (2001).
100. Carlson, J. M. & Doyle, J. Highly optimized tolerance: a mechanism for power laws in designed systems. *Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Topics* **60**, 1412-27 (1999).
101. Carlson, J. M. & Doyle, J. Complexity and robustness. *Proc Natl Acad Sci U S A* **99 Suppl 1**, 2538-45 (2002).
102. Barabasi, A. L. & Albert, R. Emergence of scaling in random networks. *Science* **286**, 509-12 (1999).
103. Bak, P., Tang, C. & Wiesenfeld, K. Self-organized criticality. *Physical Review. A* **38**, 364-374 (1988).
104. Lamport, L., Shostak, R. & Pease, M. The Byzantine Generals Problem. *ACM Transactions on Programming Language and Systems* **4**, 382-401 (1982).
105. Cassel, D. & Pfeuffer, T. Mechanism of cholera toxin action: covalent modification of the guanyl nucleotide-binding protein of the adenylate cyclase system. *Proc Natl Acad Sci U S A* **75**, 2669-73 (1978).
106. Moss, J. & Vaughan, M. Guanine nucleotide-binding proteins (G proteins) in activation of adenylyl cyclase: lessons learned from cholera and "travelers' diarrhea". *J Lab Clin Med* **113**, 258-68 (1989).
107. Harris, A. L. Hypoxia--a key regulatory factor in tumour growth. *Nat Rev Cancer* **2**, 38-47 (2002).
108. Bingle, L., Brown, N. J. & Lewis, C. E. The role of tumour-associated macrophages in tumour progression: implications for new anticancer therapies. *J Pathol* **196**, 254-65 (2002).
109. Hasty, J., McMillen, D. & Collins, J. J. Engineered gene circuits. *Nature* **420**, 224-30 (2002).
110. McMichael, A. J. & Rowland-Jones, S. L. Cellular immune responses to HIV. *Nature*

410, 980-7 (2001).

111. McCune, J. M. The dynamics of CD4+ T-cell depletion in HIV disease. *Nature* **410**, 974-9 (2001).
112. Richman, D. D. HIV chemotherapy. *Nature* **410**, 995-1001 (2001).
113. Pomerantz, R. J. HIV: a tough viral nut to crack. *Nature* **418**, 594-5 (2002).
114. Dropulic, B., Hermankova, M. & Pitha, P. M. A conditionally replicating HIV-1 vector interferes with wild-type HIV-1 replication and spread. *Proc Natl Acad Sci U S A* **93**, 11103-8 (1996).
115. Weinberger, L. S., Schaffer, D. V. & Arkin, A. P. Theoretical design of a gene therapy to prevent AIDS but not human immunodeficiency virus type 1 infection. *J Virol* **77**, 10028-36 (2003).
116. Mautino, M. R. & Morgan, R. A. Gene therapy of HIV-1 infection using lentiviral vectors expressing anti-HIV-1 genes. *AIDS Patient Care STDS* **16**, 11-26 (2002).
117. von Bertalanffy, L. *General System Theory: Foundations, Development, Applications* (George Braziller Inc., New York, 1976).
118. Wiener, N. *Cybernetics: or Control and Communication in the Animal and the Machine* (The MIT Press, Cambridge, MA, 1948).
119. Doyle, J., Glover, K., Khargonekar, P. & Francis, B. State-space solutions to standard H2 and H1 control problems. *IEEE Trans. on Automat. Control* **34**, 831-847 (1989).
120. Ma, L. & Iglesias, P. A. Quantifying robustness of biochemical network models. *BMC Bioinformatics* **3**, 38 (2002).
121. Haken, H. *Synergetics - An Introdution* (Springer, 1978).
122. Prajna, S. & Papachristodoulou, A. in *Proceedings of American Control Conference* 2779 - 2784 (IEEE, Denver, CO, 2003).
123. Prajna, S., Papachristodoulou, A. & Parrilo, P. A. in *Proceedings of IEEE Conference on Decision and Control* 741-746 (IEEE, Las Vegas, 2002).
124. Chen, K. C. et al. Integrative analysis of cell cycle control in budding yeast. *Mol Biol Cell* **15**, 3841-62 (2004).
125. Martins, N. C. & Dahleh, M. A. in *Forty-Second Annual Allerton Conference on Communication, Control, and Computing* (Urbana-Champaign, 2004).
126. Martins, N. C., Dahleh, M. A. & Elia, N. in *IEEE Conference on Decision and Control* (IEEE, Nassau, 2004).
127. Prigogine, I. & Defay, R. *Chemical Thermodynamics* (Everett, Longmans Geeen, London, 1954).
128. Prigogine, I., Lefever, R., Goldbeter, A. & Herschkowitz-Kaufman, M. Symmetry

breaking instabilities in biological systems. *Nature* **223**, 913-6 (1969).

129. Prigogine, I., Nicolis, G. & Babloyantz, A. Nonequilibrium problems in biological phenomena. *Ann N Y Acad Sci* **231**, 99-105 (1974).

130. Nicolis, G. & Prigogine, I. *Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order Through Fluctuations* (J. Wiley & Sons, New York, 1977).

131. Ao, P. Potential in stochastic differential equations: novel contruction. *J. Phys. A: Math. Gen.* **37**, L25-L30 (2004).

Air Force Project Report 2005

Hiroshi Kaminaga, ZMP INC.

September 21, 2005

Chapter 1

Overview of the Modular Sensor System

A sensory system consists of many sensors and often some actuators because the more sensor there is means more information to be acquired. However, the handling of the information among different dimension makes it difficult to be an open system because information stream from the sensor is so different that makes it difficult to provide the unitary interface between them.

The proposed system resolved this problem by constructing the system distributed intelligent telemetry and centralized the decision making. The system is designed to be modular in both macro and micro structure. Since the system is modular in both hardware and software, it is expandable and configurable. For this development, we applied this system on finding and tracking the suspicious object in closed area.

The macro structure of the system is based on IP network. The sensor device and system controller is connected with 100Base-TX Ethernet. The information through the network is as follows.

- Control signal (from controller)
- POI (Point of Interest) information (from sensors)
- Telemetric data (from the sensor, on demand)

, Control signals and POI data were transmitted over UDP/IP to minimize the overhead of transmission, but TCP/IP can also be used in situation where packet loss becomes major problem.

Since the system is built on IP network, the sensory system can be applied to small room, as applied for this project, to very large scale system. By introducing gateway on the system controller, the system can even be clustered to form hierachial sensory system.

In software, all sensors are categorized into static and active sensor. The operation modes of the sensors are simplified to surveillance and tracking mode.

The software system was designed in UML (Unified Modeling Language) and object-oriented software design technique and C++ language was used to implement the software system.

Four functional sensor devices and system controller are developed. They are actuated three-dimensional visual tracking sensor, two-dimensional audio object sensor, two-dimensional multi camera visual object sensor, and satellite visual sensor.

In the following chapter, technical details of the developed system are described.

Chapter 2

System Details

2.1 System Architecture

The sensory system is built on IP network. All sensors are connected to Ethernet through network controller as shown in figure 2.1. Only the exception is the control of servo motors that are controlled directly from controller to achieve low latency. Theoretically they could be controlled through IP network as well.

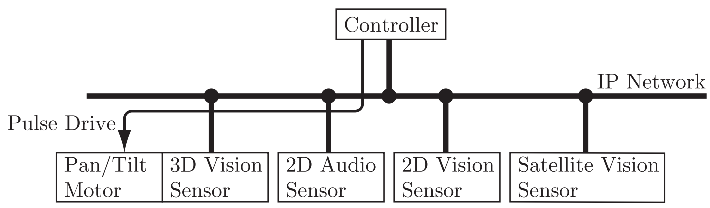


Figure 2.1: Network Structure of the System

All modules in the system are half autonomous in so that the telemetry data are reported from sensors automatically to the controller but all controls are commanded from the controller unidirectional.

The system has two operating modes, survey and tracking. In the surveillance mode, system scans through the area to find any moving object in the area. When the system finds a suspicious object, the mode switches to tracking mode to track and record suspicious object.

2.2 Sensor Fusion Processor

Sensor fusion processor, hereafter called system controller otherwise noted, receives telemetry data via IP network and commands mode transitions and motor positions. All the decisions regarding mode transitions are made in system controller.

The information reported from sensors are suspicion level and coordinate of the suspicious object. Information from sensors are prioritized then decisions are made upon given information by system controller.

2.2.1 Principle

System controller has following priority:

1. Three dimensional vision sensor
2. Two dimensional audio object sensor
3. Two dimensional vision object sensor

At the development stage now, satellite vision sensor is not yet integrated to the system that can be controlled by the system controller.

Surveillance Mode

Surveillance mode detects moving objects by background subtraction. The coordinate of the moving object is reported to the system controller. The system controller behaves as shown in figure 2.2. In surveillance mode, the controller actuates the motors on the three dimensional vision sensor to the predefined positions in predefined order and compares the aquired image with the template, which is background image averaged over time. When moving object is detected, the system moves to the detected position and tries to find moving object for special temporary position id=99. If the system finds moving object then the system switches to tracking mode to track and record the object. If it does not find any moving object then the system recovers to the preprogrammed sequence.

Tracking Mode

In tracking mode, the system tracks the object with the three dimensional vision sensor.

It has a weighing function that is highest in screen center and lowest on edges, so the sensor tracks easier to the object near to the screen center.

Putting the weighing function $w(x, y)$, coordinate of the object (x_i, y_i), and suspicion level of i-th object s_i, evaluating function is defined as follows.

$$a_i = w(x_i, y_i) \cdot s_i \tag{2.1}$$

An object which maximizes a_i is chosen to be tracked. Thus weighing function serves as a fovea which makes it easier to concentrate to object being tracked when multiple objects are detected.

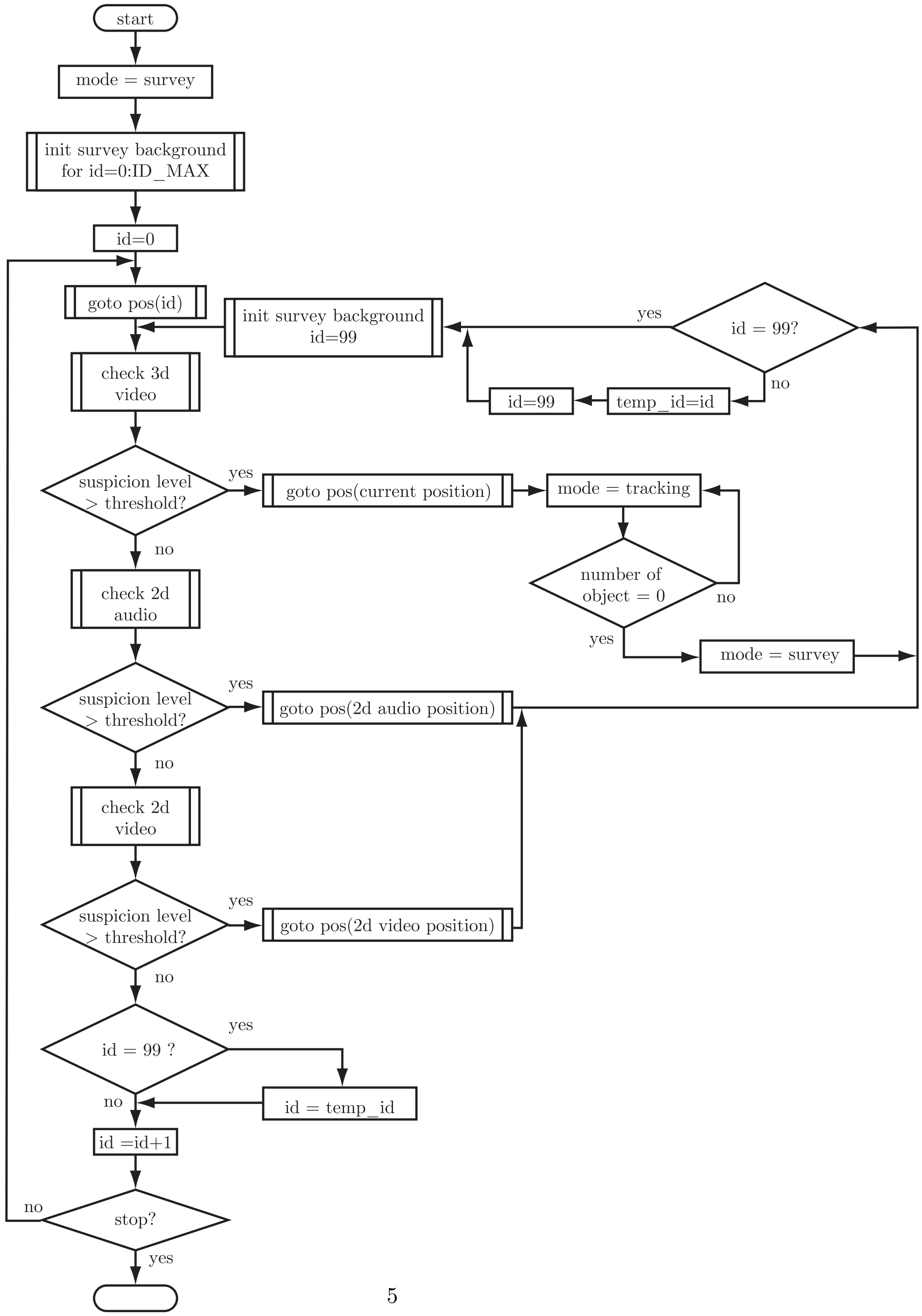


Figure 2.2: Mode Transition of the System

Let the inverse kinematics from camera position and screen position to motor angle f^{-1}, Sensor actuation algorithm is defined as follows.

$$[\theta[k+1], \phi[k+1]]^T = K \cdot f^{-1}(\theta[k], \phi[k], x_i, y_i) \tag{2.2}$$

Here, K is the proportional feedback gain.

The system has geometrical singular point at $\phi = 90deg$. To avoid the singularity, the rule $\theta = 0$ when $\phi = 90deg$ was used.

2.2.2 Software

The system controller runs on Microsoft Windows. The software is modular and new sensors can easily be added.

A structure of packet being transmitted between the system controller and each modules is shown in table 2.1.

Table 2.1: Packet Structure

Header 0
Header 1
Object 0
Object 1
⋮

Header 0 is the section that contains the summary of the sensory data. Typically it contains which sensor the packet is from, size of the packet, and number of objects detected. There are some more additional information that is sensor dependent.

Header 1 contains commands from the controller to the sensors. Now it is only used for three dimensional visual sensor, since only this sensor has tracking ability currently.

Number of object section depends on how many objects were detected. It can be any number above zero. It contains suspicion level and position of the detected object.

The packet is transmitted by UDP on specified port. The details on the packet will be discussed on each sensor.

2.3 Three-Dimensional Visual Object Tracking

Shown in figure 2.3 is the three dimensional visual object tracking sensor. This sensor's functionality are as follows:

- Acquire three dimensional depth map
- Detect suspicious object by subtracting background depth map

- Survey with preprogrammed position
- Report coordinates and degree of suspicion to controller
- Continuously report coordinates of suspicious area once tracking command is issued from controller
- Receive target motor position from controller and move to the designated position

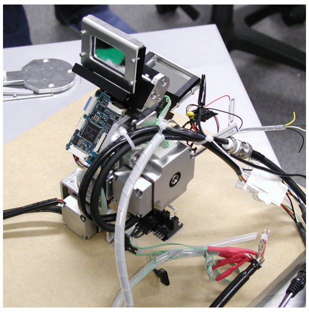


Figure 2.3: Three-Dimensional Visual Object Tracking Sensor

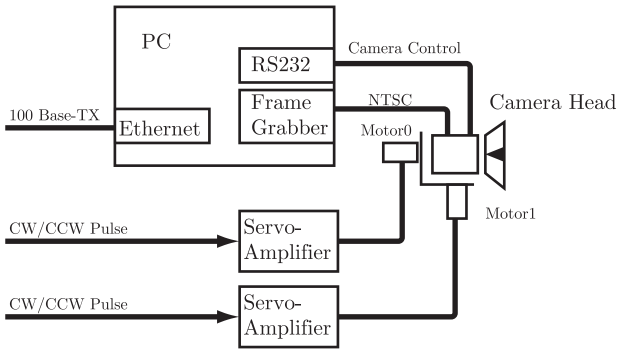


Figure 2.4: Three-Dimensional Visual Object Tracking Sensor Block Diagram

2.3.1 Principle

Three dimensional visual sensing was achieved by stereo vision. The reason for using three dimensional sensing is to be robust to the change in ambient brightness and object texture.

Stereo vision is based on range finder technique and detects distance by measuring offset in right and left image (See figure 2.5). Cross correlation or

SAD (Sum of Absolute Difference) is used to find the corresponding area on the image.

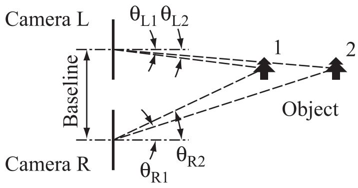


Figure 2.5: Principle of Stereo Vision

Three dimensional visual object sensing has following advantages over two dimensional object sensing.

- Ambient brightness does not affect the sensing
- Sensitivity does not change between colors

However it has following disadvantages at the same time.

1. Requires fast processor
2. Recognition is disturbed by object without texture or texture running in the direction of range finder
3. Cameras have to be calibrated
4. Camera frame must be synchronized

The cameras have to be calibrated to get equal output for equal images. Otherwise correlation of the image would be inaccurate. Camera frame must be synchronized for the same reason.

2.3.2 Optics

To resolve the item three and four of disadvantage, single camera was used to acquire the image. Field of view was splitted in two with mirrors as shown in figure 2.6. By splitting the image in two, baseline is introduced. After capturing

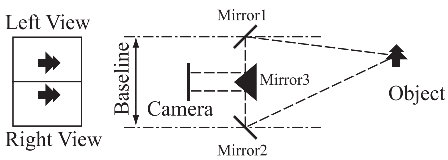


Figure 2.6: Arrangement of Mirrors

camera image, left and right view in one frame, view are splitted and treated as separate image.

Since only one camera is used, synchronization, color calibration, and brightness control is not necessary as in conventional stereo vision using two cameras.

NTSC analog CCD camera was used. The selected device is equipped with high-quality optics which is necessary to capture detailed texture which is important in calculating accurate distance. The image was captured with frame grabber in PC with Pentium 4 3GHz with hyper threading. High performance computer was needed to calculate depth in high frames rate in half VGA resolution.

2.3.3 Mechanical Structure

The sensor is equipped with a pair of motors, arranged orthogonal, making it possible to track detected object.

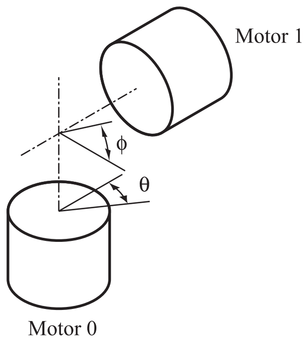


Figure 2.7: Arrangement of Motors

Pulse commanded AC servo motor with Harmonic Drive gear head was used. Harmonic Drive reducer was necessary to eliminate the vibration caused by gear backlash. In vision systems, vibration with amplitude of few tenth of degrees can easily result in vibration of few tens of pixel, which is catastrophic in constructing vision servo system. Command for motor is given by sensor fusion processor discussed in section 2.2.1.

2.3.4 Software

The three dimensional recognition engine was purchased from CyVerse Corporation [1]. The software was customized in following ways:

- Returns UDP packet in specified manner
- Detect object with both two dimensional and three dimensional calculation and reports it to the controller.

[1] http://www.cyverse.co.jp

Table 2.2: Three Dimensional Video Packet Header 0 (Status)

Field Name	Data Size(Byte)	Data Type	Description
ID	4	4 Chars	"VD" + null
Packet Size	4	Long	Size in byte including this header
Mode	4	Long	Survey/Tracking
Preset ID	4	Long	Preset ID
Suspicion Level	4	Long	0-100%
No. of Objects	4	Long	Number of detected objects
Empty	8		N/A

Table 2.3: Three Dimensional Video Packet Header 1 (Command)

Field Name	Data Size(Byte)	Data Type	Descripton
Mode Switch	4	Long	-1:default, 0:surveillance, 1:tracking
Preset Check	4	Long	-1:default 0-n: Preset ID to be checked
Init Preset	4	Long	-1:none 0-n: Preset ID to be initialized
Empty	20		N/A

2.4 Two-Dimensional Audio Object Sensing

Figure 2.8 shows the structure of two dimensional audio object sensor.

This sensor has following functionality:

- Detection of sound above specified level
- Eliminate background noise by adaptive filtering
- Calculate position of sound source
- Report position of sound source and sound level to the controller

2.4.1 Principle

Sound sensor is two dimensional microphone array. Position of the sound source is defined by angle of source as shown in figure 2.10. [2]

[2]Technically it is possible to calculate the coordinate of the sound source in x and y, but considering about the accuracy of the localization and field of view of the three dimensional

Table 2.4: Three Dimensional Video Packet Object

Field Name	Data Size(Byte)	Data Type	Description
Suspicion Level	4	Float	0-100%
Position X	4	Float	±1.0 relative position from screen center
Position Y	4	Float	±1.0 relative position from screen center
Distance	4	Float	meter
Empty	16		N/A

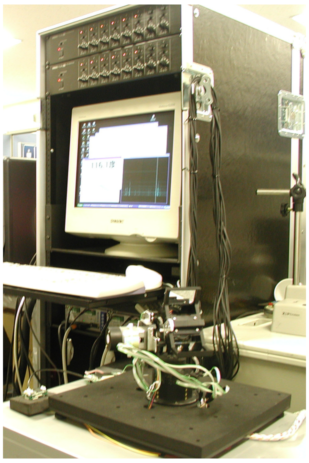


Figure 2.8: Two-Dimensional Audio Object Sensor

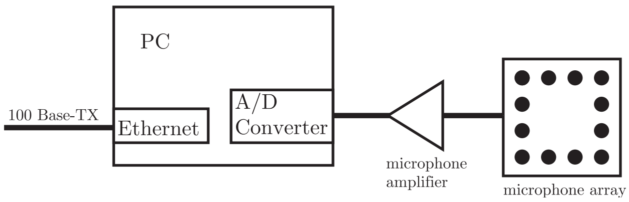


Figure 2.9: Two-Dimensional Audio Object Sensor Block Diagram

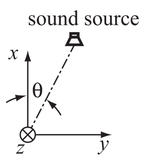


Figure 2.10: Sound Source Position

Let us start from the sound source identification using linear microphone array (See figure 2.11). When a sound is generated at point A, there would

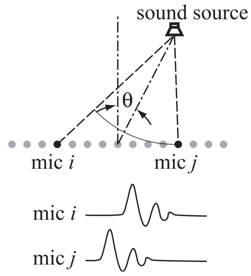


Figure 2.11: Linear Microphone Array

be a phase delay in sound wave among microphone array due to the difference in distance from the sound source. The difference distance can be calculated from the phase delay and speed of sound. Assuming the "standard" ambient condition, 20 degrees Celsius and 1bar, the distance can be calculated with some accuracy. From this difference in the distance, position of the sound source can be localized.

We extended this idea to two dimensional microphone array.

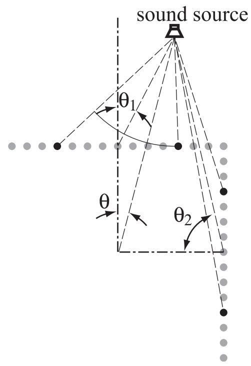


Figure 2.12: Two Dimensional Microphone Array

With the configuration shown in figure 2.12, angles from two adjacent microphone array can be calculated and therefore coordinate of the sound source can be localized.

---

vision sensor (we assumed the usage with vision sensor because those sensors can be complementary), it was thought to be reasonable just calculating the angle of the source. In cases such as camera mounted five meters high ceiling with room size over $20 \times 20m^2$, it can be reasonable to calculate the coordinate.

The phase difference is calculated by taking cross correlation with central microphone every 256 milli-seconds. Two adjacent microphone arrays are chosen by comparing maximum sound intensity of the microphone array. The advantage of using cross correlation is that the signal level of the microphones do not have to be adjusted accurately. Since the calculation of phase difference is done in time domain, theoretically difference in signal intensity between microphones does not affect the result. However, it has to be adjusted to the level that it can identify the position of the sound source from the intensity difference to decide which two adjacent microphone arrays to be used.

The noise filtering is done by eliminating background noise bandwidth after FFT'ing the captured waveform then inverse FFT was used to get time domain waveform. This method was chosen due to the hardware support of FFT in microprocessor that could reduce the calculation load by 70%. With microprocessor with vector support, FIR may also be useful.

2.4.2 Audio Sensor

Twelve microphones are used in the microphone array; four on each side, sharing the corner microphone. Microphones are connected to amplifier to adjust signal level.

All of the microphone signals are then captured with A/D converter PCI card. A/D converter card with simultaneous capturing capability was chosen to guarantee the accuracy of phase delay detection.

2.4.3 Mechanical Structure

Microphones are arranged as shown in figure 2.13.

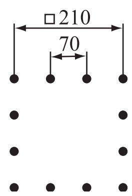


Figure 2.13: Arrangement of the Microphones

They are fixed in formed rubber to isolate from the vibration and avoid the reflection from the fixation surface. As mentioned in prior section, microphone array was chosen as a complementary sensor to the three dimensional vision sensor. Therefore the microphone array is placed around the three dimensional vision sensor.

Purely from the accuracy point of view, the pitch of the microphone should be as long as possible because the phase delay becomes larger that makes the measurement more accurate. similarly, number of the microphones should be as much as possible to average out the measurement error. However, in reality, the size of the array is limited considering the usage such as fixing it onto the ceiling. Also, number of microphones are limited by the capturing channel of the capture device. The pitch of the microphone was chosen from the calculation of sampling rate of the capture device and speed of sound to have enough time resolution. Number of microphones was chosen so the microphone array becomes axis symmetric and still less than the number of channels in conventional capture card which is sixteen.

2.4.4 Software

The software was developed together with Harada Laboratoy in Tokyo University of Science [3]. The sound localization was done on PC with Pentium 4 2GHz. Intel's Math Kernel Library was used to make use of microprocessor dedicated commands to enhance the arithmetic performance.

Two dimensional audio sensor is categorized as static sensor. It reports the coordinate of the sound and sound level to controller in following packet format.

Table 2.5: Audio Packet Header 0

Field Name	Data Size(Byte)	Data Type	Description
ID	4	4 Chars	"AD" + null
Packet Size	4	Long	Size in byte including this header
Mode	4	Long	N/A
Preset ID	4	Long	N/A
Suspicion Level	4	Long	0-100%
No. of Objects	4	Long	N/A
Empty	4		N/A

Table 2.6: Audio Packet Header 1

Field Name	Data Size(Byte)	Data Type	Description
Empty	32		N/A

2.5 Two-Dimensional Visual Object Sensing

Figure 2.14 shows the structure of two dimensional visual object sensor.

This sensor has following functionality:

[3] http://www.te.noda.sut.ac.jp/pub/labs/harada/index-j.html

Table 2.7: Audio Packet Object

Field Name	Data Size(Byte)	Data Type	Description
Suspicion Level	4	Float	0-100%
Position	4	Float	±180 deg
Empty	24		N/A

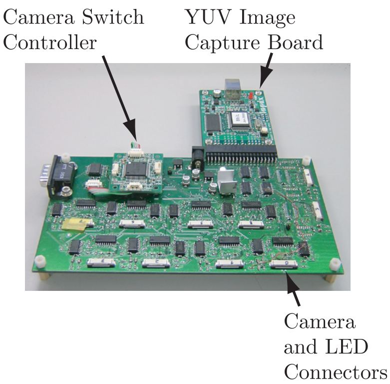


Figure 2.14: Two-Dimensional Visual Object Sensor

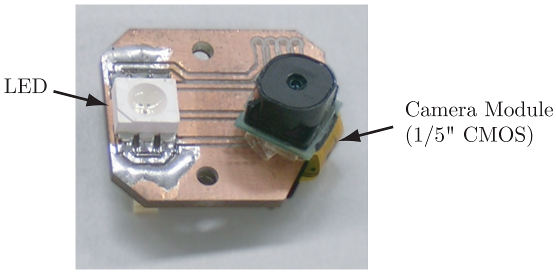


Figure 2.15: Camera Module

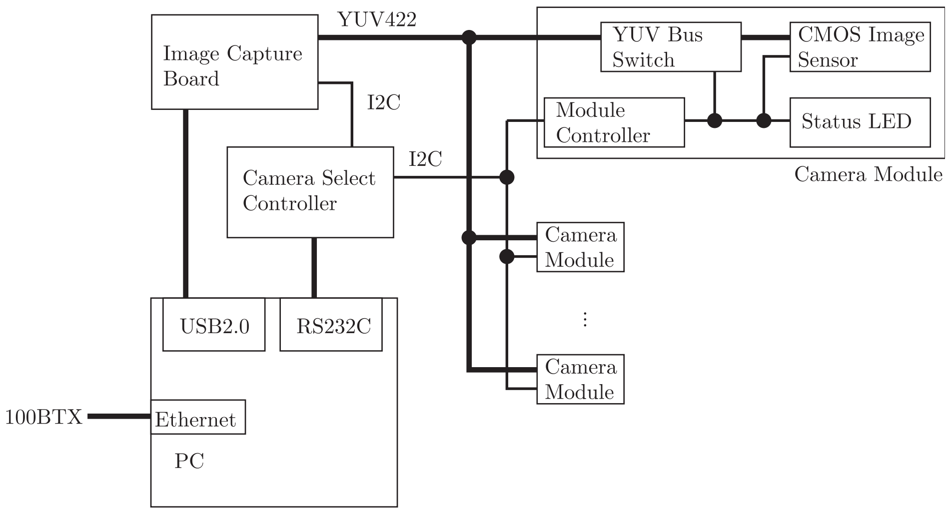


Figure 2.16: Two-Dimensional Visual Object Sensor Block Diagram

- Detection of motion in screen by background subtraction
- Eliminate background fluctuation by adaptive filtering
- Calculate position of moving object
- Report position of moving object and suspicion level to the controller

2.5.1 Principle

In comparison to the three dimensional vision sensor, two dimensional vision sensor is equipped with fixed multiple cameras to aquire images from all direction.

Since the cameras don't move, surveillance can be done with least power and operation can be done without being know by people who broke in. Images from multiple cameras are aquired by time sharing. Sensor controller switches between cameras to scan through the room.

Detection of the suspicious object is done with two dimensional image comparison. Background image is averaged over specified time to reduce error reduction caused by change in brightness or lighting condition. Position of each cameras must be preprogrammed in the system controller for the system controller to know which way to point the three dimensional vision sensor when switching to tracking mode.

VGA(640x480) resolution CMOS image sensor was used as the camera device. The output from the camera is parallel 8bit YUV422 and control of the device is done through I2C.

2.5.2 Software

Table 2.8: Two Dimensional Video Packet Header 0

Field Name	Data Size(Byte)	Data Type	Description
ID	4	4 Chars	"CA" + null
Packet Size	4	Long	Size in byte including this header
Mode	4	Long	N/A
Preset ID	4	Long	N/A
Suspicion Level	4	Long	0-100%
No. of Objects	4	Long	Number of detected objects
Empty	4		N/A

Table 2.9: Two Dimensional Video Packet Header 1

Field Name	Data Size(Byte)	Data Type	Description
Empty	32		N/A

Table 2.10: Two Dimensional Video Packet Object

Field Name	Data Size(Byte)	Data Type	Description
Suspicion Level	4	Float	0-100%
Camera ID	4	Long	ID of camera detected the object
Position X	4	Float	± 1.0 relative position from screen center
Position Y	4	Float	± 1.0 relative position from screen center
Empty	16		N/A

2.6 Satellite Visual Sensor

Figure 2.17 shows the structure of satellite video sensor.

This sensor has following functionality:

- Streaming of Motion JPEG over Ethernet
- Streaming of video data over 3G-324M (video phone)

Figure 2.17: Satellite Visual Sensor

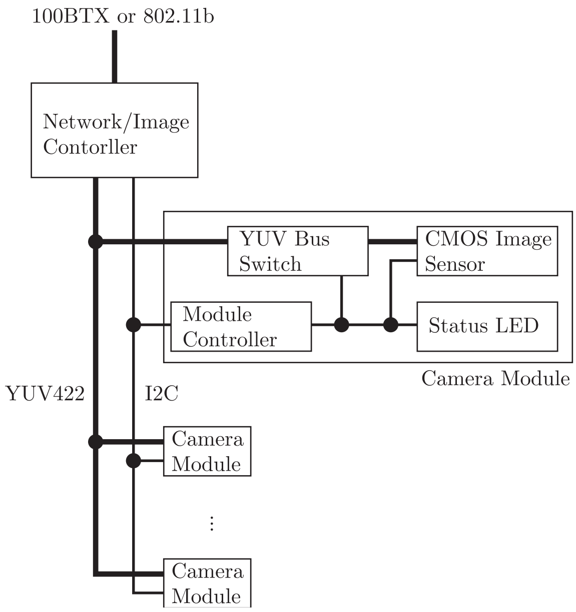


Figure 2.18: Block Diagram of the Satellite System

2.6.1 Principle

As seen from figure 2.18, basic operating principle is similar to that of two dimensional vision sensor. Except in satellite sensor, in order to pack all the hardware functionality in to a hemisphere with diameter of 120mm, hadware layout is very different.

Modules connected currently are only image devices, but the architecture supports other sensors such as PIR sensors and temperature sensors.

Network controller captures YUV data transmitted from cameras and encodes it to either MPEG-4 or Motion JPEG. Network media is 100 Base-TX by default but IEEE 802.11b wireless lan and video phone access via 3G-324M is also supported.

Unlike other sensor modueles, satellite vision sensor can be operated standalone. Right now, object detection and integration to the system are not implemented on this module.